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PAPERS IN PRESS FOR FORTHCOMING ISSUES

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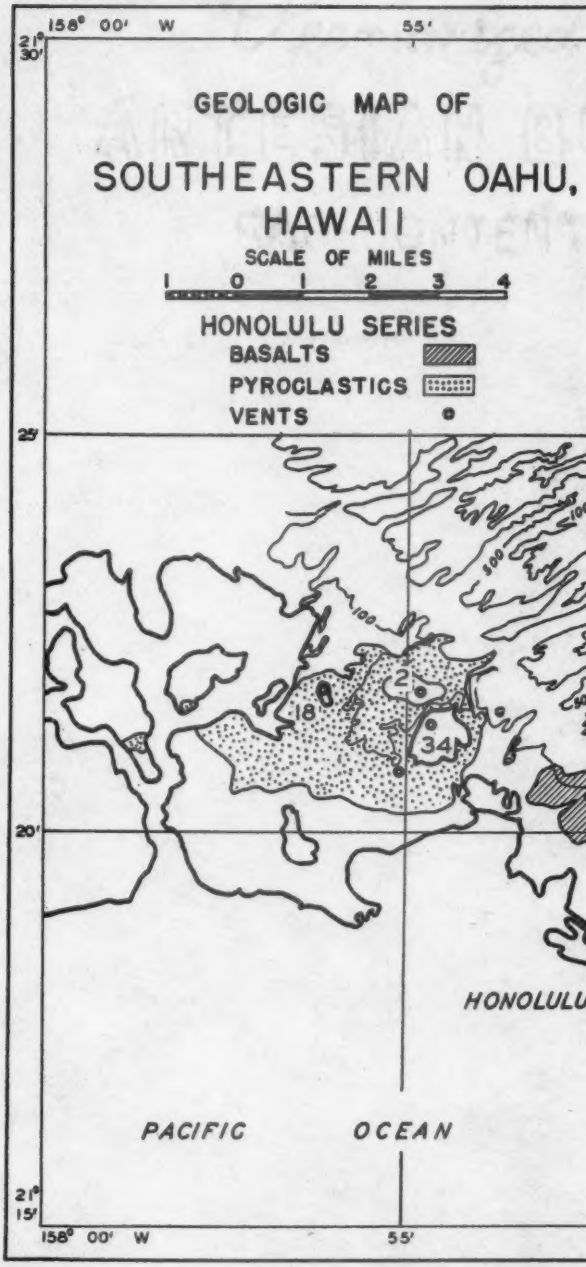

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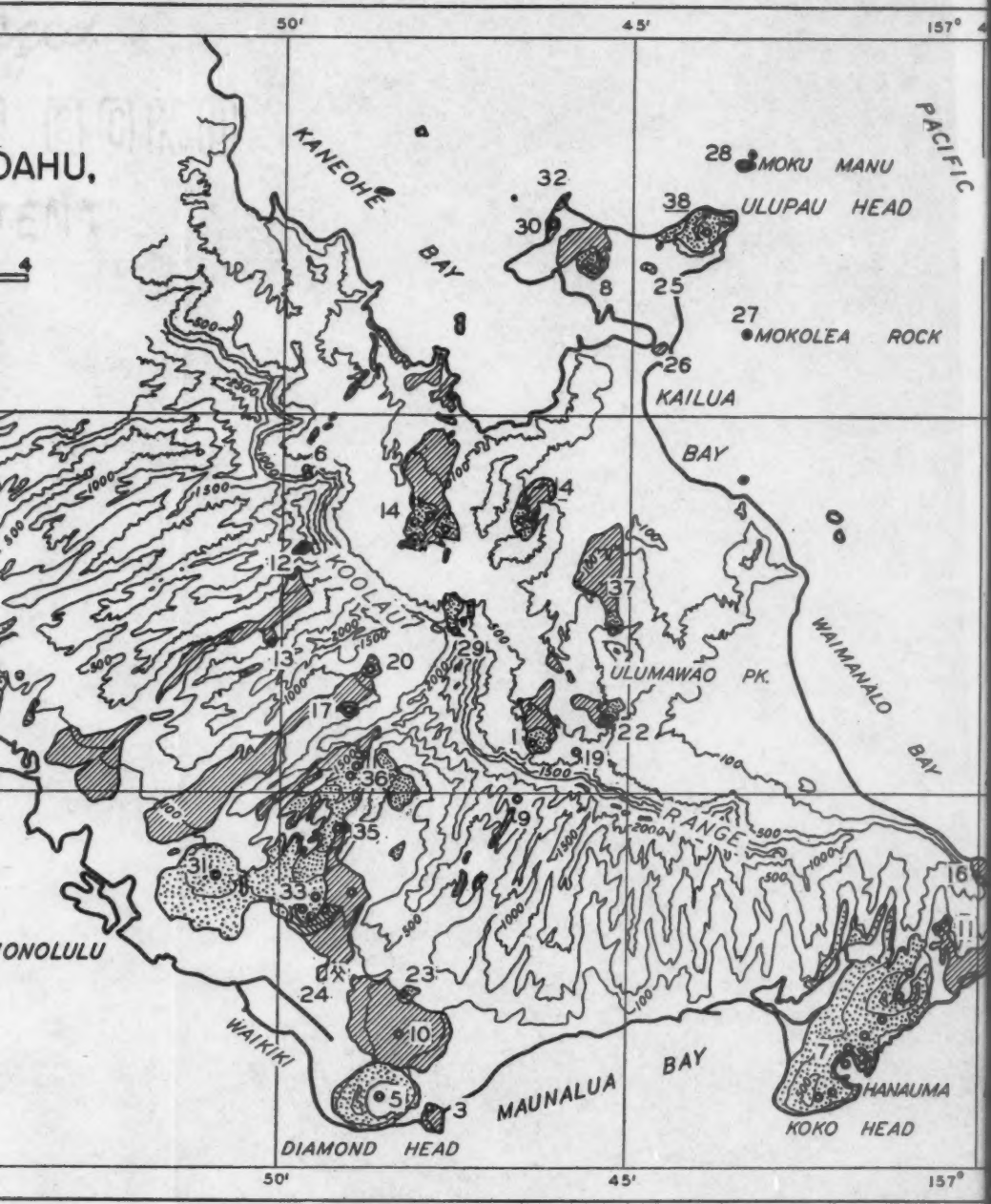

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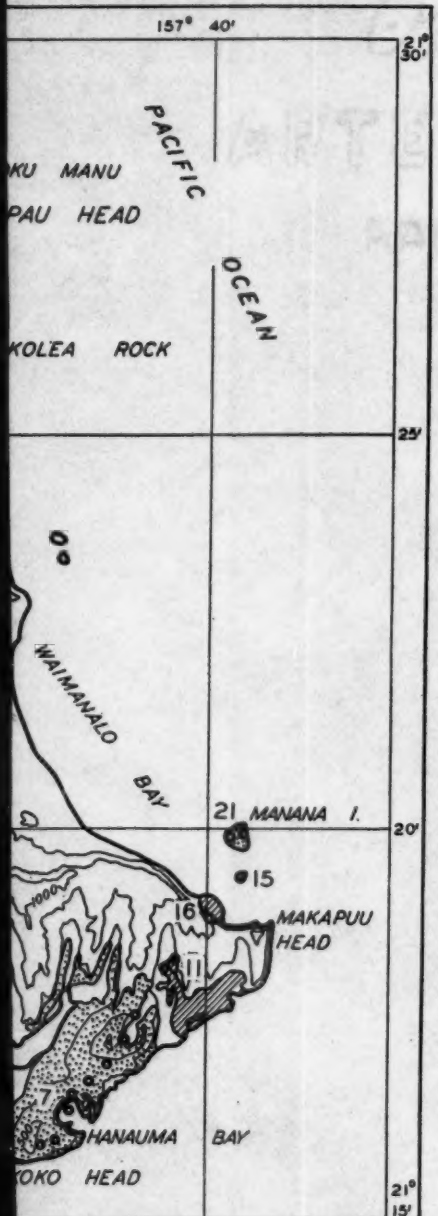
GEOLOGIC MAP OF SOUTHEASTERN OAHU

Showing locations and names of vents and lavas of the Honolulu series. After Stearns (1939)



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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
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HONOLULU SERIES, OAHU, HAWAII

BY HORACE WINCHELL

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ABSTRACT

The Honolulu series comprises about 30 distinct, separate eruptions of nepheline basanite, nepheline basalt, and nepheline-melilite basalt which occurred in late Pleistocene and Recent time in the southeastern part of the Koolau Range of Oahu. The

unconformity between the Honolulu series and the underlying, internally conformable Koolau series which probably forms more than 99 per cent of the bulk of the Koolau Range represents a long erosion interval, since a relief of about 2000 feet was developed. The work of Stearns and Vaksvik (1935) covering all Oahu is the starting point for detailed descriptions of the areal and structural geology of the Honolulu series.

Eight new analyses supplement the petrographic description of the rocks. No theory of differentiation yet advanced seems to account fully for the origin of these lavas. In particular, limestone syntexis is shown to be out of the question. Mineralizers are present and were present in larger quantity during the differentiation but are too imperfectly understood for an adequate discussion. Crystallization differentiation offers difficulties unless the rather improbable separation of hypersthene is postulated instead of olivine, from the primitive olivine basalt magma typical of Hawaii. There is no evidence for crystallization differentiation in place following extrusion, and none was found to indicate systematic variations in successive flow units from a given vent.

INTRODUCTION

PURPOSE AND SCOPE OF THE STUDY

The Honolulu series constitutes a volumetrically insignificant, but petrographically important, group of lavas whose origin has not been satisfactorily explained. These lavas were extruded during a late Pleistocene and Recent renewal of volcanic activity in the southeastern part of the Koolau (northeast) Range of Oahu, in the vicinity of Honolulu. They rest unconformably on the Koolau series which is the basement rock formation of the Koolau Range. The interval of erosion suggested by this unconformity is long, as shown by the great relief developed.

A detailed study of the occurrence and petrology of these posterosional lavas is the primary subject of this paper. Chemical analyses of eight flows belonging to the Honolulu series are presented, together with data that will enable one to revisit the exact locality where each was collected. Photographs of the outcrops from which the specimens were collected may be consulted in the files of the Board of Water Supply at Honolulu, in the photographic files of C. K. Wentworth and of the writer, and in the library of Harvard University (Winchell, H., 1941), where a more detailed description of each locality will also be found.

This paper accompanies and supplements one by Wentworth and Winchell (1946) on the Koolau series. Frequent references are made to that paper, particularly to the tables.

ACKNOWLEDGMENT

The field work and much of the thin-section work were done as part of the official survey of the geology and water resources of the Honolulu District, under Dr. C. K. Wentworth, for the Board of Water Supply of Honolulu. Doctor Wentworth and Mr. Frederick Ohrt, Chief Engineer of the Board of Water Supply, provided an unsurpassed opportunity to study the rocks at close range, both in the field and in the laboratory. New chemical analyses reported in this paper were made by F. A. Gonyer, Harvard University, under Grant 297–39 of the Penrose Bequest of The

Geological Society of America to the Committee on Hawaiian Petrology.[1] The author is particularly indebted to Professor E. S. Larsen, Harvard University, for his comments and criticisms during the latter part of the work, which was done in his laboratory at Harvard.

TABLE 1.—*Ancient shore lines known in Hawaii*

Age	Name	Elevation (Feet)
Tertiary	Lualualei	*ca.* −1800
	Mahana	*ca.* 1200
	Manele	560
	?Olowalu	*ca.* 250
Quaternary	Kahuku	55
	Kahipa	*ca.* −300
	Kaena	95
	Laie	70
	Waipio	*ca.* −60
	Waimanalo	
	upper—27 feet	25
	lower—22 feet	
	Kapapa	5
	Modern	0

Sources: Stearns (1935a; 1935b; 1938; 1939, p. 10); Stearns and Vaksvik (1935, p. 47–48).

GEOLOGY OF SOUTHEASTERN OAHU

STRATIGRAPHY

The geology of the Koolau Range of mountains is not complex. A basement series of hypersthene-bearing basalts composes the Koolau Range which forms the northeastern part of Oahu. These rocks are treated in detail in the companion paper, *The Koolau series*. They are mainly olivine- and hypersthene-bearing basalts, slightly more silicic than most Hawaiian basalts. The Koolau series is cut by swarms of dikes along most of the length of the Koolau Range, forming a dike complex which has been mapped in some detail by Stearns (1939) and which is shown by Wentworth and Winchell (1946, Fig. 1). A supposed caldera-filling series in an old, buried Koolau caldera is exposed in the vicinity of Kailua.

Following the dome-building period of the Koolau volcano there was a long period of erosion during which relief of the order of 2000 feet was developed in the southeastern part of the Koolau Range, and the topographic crest of the range was shifted toward the leeward side, with the reduction of the windward side considerably below its original surface. During this time, changes of sea level resulted in the formation of terraces graded to various base levels. In late Pleistocene and Recent time volcanic activity was locally renewed, and the resulting Honolulu series was extruded in sporadic flows that are now interbedded with the sediments.

Since the cessation of volcanic activity there has not been enough time for appre-

[1] W. O. Clark, E. S. Larsen, H. S. Palmer, H. A. Powers, H. Winchell, and C. K. Wentworth, *Chairman*.

TABLE 2.—*Geochronology of Oahu*

TERTIARY		
Waianae dome growth and earliest Koolau dome growth		
Extinction of Waianae volcano; overlapping by Koolau volcano		
EARLY (?) PLEISTOCENE		
Extinction of Koolau volcano; very long erosion interval		
Lualualei (−1800-foot) stand (evidence on Oahu)		
MIDDLE (?) AND LATE PLEISTOCENE		
Mahana (1200-foot) stand (evidence on Lanai, traces on Oahu)		
Manele (560-foot) stand (evidence on Lanai, traces on Oahu)		
Olowalu (250-foot) stand (evidence on Maui, traces on Oahu)		
Kahuku (55-foot) stand		
	Honolulu series	
	Stearns-Vaksvik	(Winchell)
Kahipa (−300-foot) stand		Hawaiiloa
		Pali Kilo
		Pyramid Rock
		Moku Manu (?)
		Ulupau (?)
		Mokolea (?)
Kaena (95-foot) stand	Hawaiiloa	Kalihi
	Mokapu	Haiku
	Mokolea	Rocky Hill
	Rocky Hill	Aliamanu
	Kalihi	Kaneohe
	Haiku	Luakaha, Makuku } Nuuanu
	Aliamanu	
	Kaneohe	Pali
	Nuuanu	(Makawao = Koolau?)
	Pali	Kaau
	Makawao (Koolau?)	
	Moku Manu	
Laie (70-foot) stand	Ulupau	Mauumae
	Kaau	
Waipio (−60-foot) stand	Salt Lake and Makalapa	Salt Lake and Makalapa
	Ainoni	Ainoni
	Maunawili	Castle
	Training School	Maunawili
	Diamond Head	Training School
	Kaimuki	Diamond Head
	Mauumae	Kaimuki
	Black Point	Black Point
	Kamanaiki	Kamanaiki
	Punchbowl	Punchbowl
Waimanalo (25-foot) stand	Castle (Waipio?)	
LATEST PLEISTOCENE OR RECENT		
?Kapapa (5-foot) stand, Modern stand	Koko group	Koko group
	Tantalus group	Tantalus group

Sources: Time scale—Stearns, 1935b; 1938; 1939; Stearns and Vaksvik, 1935. Honolulu series—Stearns and Vaksvik, 1935; Winchell, H., field notes, 1938–40.

ciable erosion or deposition. No legends suggest activity since the arrival of the earliest Hawaiians several centuries ago.

TIME SCALE

The lavas and pyroclastic rocks of the Honolulu series should be dated more accurately than available fossil evidence permits if a useful sequence is to be obtained. Sedimentary deposits on Oahu can be related to a series of different sea levels possibly due in part to eustatic changes connected with the advance and retreat of the ice caps during Pleistocene time. Some of the changes of sea level relative to the island were probably due to isostatic adjustments of its crustal segment in response to the load of the extruded Koolau and Waianae basalts.

Table 1 shows the ancient shore lines postulated by Stearns in describing the geology of Oahu and other Pacific islands. They are identified mainly by geomorphic evidence. The differentiation of the Waimanalo and the Kapapa stands of the sea is controversial but has little significance for the purposes of this discussion.

The geologic history of Oahu, especially concerning eruptions of the Honolulu series, may be related to this scale as shown in Table 2. After the first appearance of the Honolulu series two interpretations are given. The differences are more apparent than real, since Stearns and Vaksvik show some indecision in their interpretations of the data (1935, p. 99–165; Stearns, 1939; 1940). The events did not necessarily take place in exactly the order named. They probably occurred in the groups indicated by the different stands of the sea; but the order within such groups is rarely determinable with assurance. In a few cases even the group may be in question.

LAVA FLOWS OF THE HONOLULU SERIES

KAHIPA (−300-FOOT) STAND OF THE SEA

General statement.—The earliest group of Honolulu series eruptions probably took place some time prior to the Kaena stand of the sea at 95 feet. Therefore they are assigned to the Kahipa stand at −300 feet.

Hawaiiloa, Pali Kilo, Pyramid Rock, and Moku Manu.—Hawaiiloa, Pali Kilo, Pyramid Rock, and a 71-foot hill between the last two are prominences composing a large part of Mokapu Peninsula (Pl. 1). Moku Manu is the name of two small islets off the north shore of the peninsula. Puu Hawaiiloa is a scoria and cinder cone from which a large nepheline-melilite basalt lava flow extends northward to, and probably beyond, the present sea shore. The subaerial character of the flow surface and the apparent erosion of the cinder cone by the Kaena (95-foot) sea form the principal evidence for assigning the eruption to the Kahipa (−300-foot) stand. Similar evidence suggests a like age for the vents on a line from Pali Kilo to Pyramid Rock, forming the western shore of the peninsula. Stearns and Vaksvik (1935, p.100) stated that the lava mass making up the hills on this line probably formed part of the Puu Hawaiiloa lava flow although now separated from it. Stearns later (1940 p. 50–51) changed this interpretation but stated that the lavas of Puu Hawaiiloa

and of the Pali Kilo group are "similar in mineral composition, but different in texture." He did not note the considerable proportion of melilite present at least locally in the Hawaiiloa flow. Neither Stearns nor the writer found melilite in the lavas from the Pali Kilo group. New evidence of vent activity at Pali Kilo and at Hill 71 should be recorded here. Lava balls similar to those described by Stearns and Vaksvik (1935, p. 159) in connection with known vents elsewhere can be found on the slopes of Pali Kilo and also near the summit of Hill 71. The presence of such balls of dense lava is interpreted as confirmatory (although not conclusive) evidence of the existence of vents at these hills. The relative age of these vents and of Puu Hawaiiloa vent is unknown.

Moku Manu islets antedate the Waimanalo (25-foot) stand of the sea. They are probably older than Ulupau Head tuff cone, since tuff similar to that of Ulupau Head occurs on them (Stearns and Vaksvik, 1935, p. 120). A lava specimen from Moku Manu furnished by Dr. C. K. Wentworth is nepheline basalt with no feldspar or melilite; it is similar to Pali Kilo lava but not to that of Puu Hawaiiloa. Tuff, cinders, a crater-filling lava plug, and a few sedimentary deposits probably laid down in the Waimanalo (25-foot) sea occur on the islets.

Ulupau Head and "Mokapu basalt".—Ulupau Head tuff cone is the highest feature on Mokapu Peninsula. It forms the northeast headland opposite Moku Manu. Stearns and Vaksvik described two outcrops they named "Mokapu basalt" located on the peninsula as shown in Plate 1. The northern outcrop was previously mapped by Wentworth (1926, Fig. 24). It is composed of nepheline basalt without melilite. The southern outcrop, however, is nepheline-melilite basalt. The two are therefore probably parts of different bodies; the southern one will be considered with Mokolea Rock, below. Nepheline basalt similar to the northern outcrop was found by Wentworth and Hoffmeister (1939, p. 1560) near Mokapu Landing. Powers (1920, p. 273) reported that Ulupau Head tuff is derived from melilite-nepheline basalt magma; and Stearns and Vaksvik (1935, p. 196) stated that Wentworth (1926) found melilite-nepheline basalt at Ulupau Head. Specimens of Ulupau tuff show no melilite in thin section. The dikelike mass near Mokapu Landing and the northern outcrop of the "Mokapu basalt" are nearer Ulupau Head than any other known vent and likewise show no melilite in thin sections. They are not necessarily Ulupau lava but are so considered here. Since neither the lavas nor the tuff itself contain melilite, the Ulupau tuff was probably derived from nepheline basalt magma.

No evidence has been found of primary submarine deposition of Ulupau tuff. The vent therefore erupted during a low stand of the sea. A nip at 70 feet shows that the tuff probably existed before the Laie (70–foot) stand of the sea. The first low stand prior to Laie time was the Kahipa (−300-foot) stand, with which Ulupau Head is tentatively correlated. The intervening Kaena (90-foot) stand of the sea should have left its record, but none has been found (Wentworth and Hoffmeister, 1939, p. 1568). Some Ulupau tuff is plastered on the slopes of Puu Hawaiiloa (Wentworth, 1926, p. 88; Stearns and Vaksvik, 1935, p. 100). It therefore postdated Hawaiiloa, Moku Manu, and probably Pali Kilo eruptions and belongs to the Kahipa stand.

Mokolea Rock and "Mokapu basalt".—Mokolea Rock (Pl. 1) in Kailua Bay is

made up of nepheline-melilite basalt and a little reef formation probably deposited in the Waimanalo (25-foot) sea. Stearns and Vaksvik (1935, p. 195, Spec. F-296) reported finding the following minerals in Mokolea lava: abundant phenocrysts including olivine and strongly zoned augite, and a groundmass composed of pyroxene, nepheline, melilite, magnetite, and accessory apatite. Except for the limestone, 25 feet in elevation, there is almost nothing on which to base an age estimate of Mokolea Rock. Without evidence of submarine activity, and considering the deeply weathered condition of the rock, Mokolea lava is probably of Kahipa (−300-foot) age. Stearns and Vaksvik did not note the similarity in mineral composition between Mokolea Rock and the southern "Mokapu basalt" outcrop, nor the dissimilarity of the southern and northern outcrops. Published soundings in Kailua Bay are not sufficient to prove, but do suggest, a submarine ridge between Mokolea and the shore of Mokapu Peninsula in the vicinity of the southern outcrop (U. S. C. G. S. Chart 4110). Such a ridge should be expected if the two rocks are parts of a sea-severed lava flow.

KAENA (95-FOOT) AND LAIE (70-FOOT) STANDS OF THE SEA

General statement.—The earliest eruptions that took place during a high stand of the sea belong to Kaena or to Laie time. Owing to difficulty in recognizing evidence separating them, eruptions assigned to either may equally well belong to the other. During the recession of the sea from the Kaena (95-foot) stand to the Waipio (−60-foot) stand, a bench was left at about 70 feet above present sea level. The bench is exposed near Laie village and was named for it. This may represent a short halt in the regression. Only two eruptions belonging to the Honolulu series have been tentatively assigned to the Laie stand—the Kaau and the Mauumae eruptions.

Kalihi and Haiku.—Three vents near the summit of the Koolau Range at the heads of the two opposite theater-headed valleys of Kalihi and of Haiku streams, respectively, gave rise to the lavas, cinders, and tuffs which were mapped by Stearns and Vaksvik (1935, p. 103, 106) as the Kalihi and Haiku volcanics (Pl. 1). The Kalihi lava flow is conspicuous for its olivine nodules and coarse-textured pegmatoid veinlets. Somewhat similar phases are present in the Haiku flow. Figure 3 of Plate 2 is a composite photomicrograph across the boundary of one of the pegmatoid veinlets in the Kalihi flow. It shows the remarkable variation in grain size, and to a lesser extent the concentration of some of the rarer minerals, especially analcime and apatite, that are characteristic of these pegmatoid bodies. Concentrations of ore grains (magnetite and ilmenite) have also been found in the Kalihi flow. A pegmatoid segregation in the Haiku flow, found in the stream channel below the junction of the main north and south forks, contains a similar remarkable assemblage of apatite, nepheline, analcime, perofskite, and a few tiny flakes of biotite. The lava of both flows is nepheline-melilite basalt.

The relative ages of the Haiku and Kalihi rocks cannot be determined. Both formations include lavas buried under considerable thicknesses of very old alluvium in which terraces appear to exist, graded to the Kaena (95-foot) stand of the sea. A thin bed of similar alluvial material lies under the lowest exposed Kalihi flows and

FIGURE 1. BOMB SAG IN TUFF AT KOKO HEAD
(Negative 12701)

FIGURE 2. MANTLE BEDDING OVER GULLIED SURFACE IN TUFF AT KOKO HEAD
(Negative 12692)

FIGURE 3. COMPOSITE PHOTOMICROGRAPH OF KALIHI LAVA
Textural variations at a veinlet near a pegmatoid portion of Kalihi nepheline-melilite basalt flow. N nepheline, P pyroxene, A apatite, M ore. (Section W-314, Negatives 4004)

MINOR STRUCTURES AT KOKO HEAD; KALIHI LAVA

probably indicates that the eruption took place during, not before, the Kaena stand. Stearns and Vaksvik tentatively dated the Haiku eruption in Kaena time because of the presence of pillow structures in some outcrops of Haiku lava near the shore of Kaneohe Bay. For petrographic, stratigraphic, and structural reasons the Kalihi and Haiku eruptions are probably of the same age.

Rocky Hill.—Some low mounds and craterlike depressions in lower Manoa Valley east of Punahou School have been assumed by various writers to be cinder and scoria cones. They are related to Rocky Hill, a conspicuous cone located on the northeast edge of Punahou School grounds (Pl. 1). Wentworth (1926, p. 73, 75, 92) considered them all parts of a line of vents which he named the Manoa Dike, believing they represent viscous upwellings of the magma along this dike. Evidence was later found that Rocky Hill is older than the surrounding Sugar Loaf lava flow which covers most of the bottom of Manoa Valley and extends upon the coastal plain atop the Waimanalo (25-foot) reef (Stearns and Vaksvik, 1935, p. 101). The new interpretation makes Rocky Hill and its associated vents a series of kipukas (Hawaiian: an "island" of older terrane surrounded by a lava flow—Stearns and Clark, 1930, p. 45) in the Sugar Loaf flow instead of the source of the flow as originally suggested by Hitchcock (1900, p. 46). The age of Rocky Hill is not reliably known. Stearns and Vaksvik (1935, p. 102) have assigned it to the Kaena (95-foot) stand of the sea; this interpretation is accepted for the present. The lava contains no feldspar, but considerable amounts of nepheline, augite, and olivine, with lesser amounts of ore minerals, melilite, apatite, glass, and secondary minerals.

Aliamanu.—Three prominent craters lie on the coastal plain east of Pearl Harbor (Pl. 1). These are Salt Lake (Aliapaakai), Aliamanu, and Makalapa. Another lies south of Salt Lake Crater, and there may be still others buried in the tuff of the latest eruptions. Both Aliamanu and Salt Lake craters may be doublets. Dana (1849, p. 245–248) described these craters but failed to note the presence of two tuff formations separated by an erosional unconformity. Hitchcock (1900, p. 40) found the unconformity and described the correct sequence of deposits in the region as follows: (1) main coral reef, (2) thin tuff layer, (3) coral reef or limestone, (4) decomposed rocks with soil and forest cover, (5) Salt Lake Crater, (6) time for cutting Moanalua gorge. He described Aliamanu Crater but apparently did not suspect that it was the source of the earlier tuff. Wentworth (1926, p. 60–72) included Aliamanu in the "Salt Lake Crater Group," recognized the unconformity, and suspected but could not prove that the earlier tuff was from Aliamanu. Makalapa and Salt Lake craters probably erupted simultaneously much later. Stearns (1940, p. 55) reported some buried melilite-nepheline basalt associated with the Aliamanu tuff. He had previously dated it by means of a terrace graded to the Kaena (95-foot) stand of the sea (Stearns and Vaksvik, 1935, p. 109). The Aliamanu tuff is grayish-brown palagonitic material with numerous olivine crystals and some augite and magnetite.

Kaneohe.—Kamehameha Highway passes through several large road cuts in a group of cinder cones about 2 miles south of Kaneohe Village. These cones and the associated lava flow which moved northward to the sea and shifted the position of Kaneohe Stream constitute the Kaneohe volcanics (Pl. 1). The present study checked with that of Stearns and Vaksvik (1935, p. 111, 190) in regard to the rock

in an abandoned quarry near Kaneohe, which is nepheline basalt with a porphyritic intergranular texture. Another specimen of the flow collected at a massive ledge near Kaneohe Stream, 1.2 miles north of the quarry, proved to be nepheline-melilite basalt. The reason for this difference is not known. The following list shows approximate volumes of minerals in the rocks of the two localities. Percentages are visual estimates, correct within a factor of 2.

	Stearns's locality (F–72) Per cent	1.2 miles north (W–452) Per cent
Phenocrysts		
Olivine	10	10
Augite		2
Groundmass		
Pyroxene	40	20
Nepheline	35	30?
Melilite		35?
Ore	10	3+
Apatite	tr	tr
Glass	5	

Nuuanu.—At least two tuff cones are known in Nuuanu Valley (Pl. 1). They are Luakaha, on the southeast side of the valley opposite Reservoir No. 3; and Makuku, west of Reservoir No. 4. Luakaha was first found through diamond drilling conducted by the Board of Water Supply under the direction of C. K. Wentworth. It is the source of the lower Nuuanu flow which is exposed extensively along Nuuanu Stream, as at Kapena and Alapena pools. The flow probably extends at least as far as the present sea coast under a cover of sediments and reef formation since "hard basaltic rock" was reported above considerable thicknesses of sediments and reef rock by the drillers of several old water wells near Honolulu Harbor. The lower Nuuanu flow consists of nepheline basalt with a small, variable amount of melilite. The analyzed specimen described below contains about 2 per cent melilite and 20 per cent olivine as phenocrysts in a groundmass of about equal parts of nepheline and pyroxene, with subordinate ore minerals and accessory apatite.

The upper Nuuanu flow, which issued from the vicinity of Makuku cone, directly overlies the lower and is usually distinguishable from it microscopically by the presence of prominent augite phenocrysts and an appreciably larger percentage of melilite. Diamond drilling provided much valuable information about the valley fill. A line of holes put down by the Board of Water Supply was reported briefly by Wentworth (B. W.-S., 1935, p. 135–143). The following summary of notes on cores, including some not previously reported, agrees with that published by Wentworth. Layers of alluvium, tuff, cinders, scoria, and nepheline basalt with or without melilite are arranged almost at random throughout the section. The large number of layers is the most striking feature of the cores. Careful study of thin sections from all parts of the cores and also from cores brought up from other holes in Honolulu series lavas has revealed no trace of gravitative differentiation in place, although the percentages of certain minerals such as phenocrystic augite and olivine, groundmass pyroxene, and melilite vary widely and at random. The motion of the lava was probably turbulent enough to mix its constituents; and, by the time it had stopped moving, it was too viscous to permit any appreciable settling.

The field relations of the exposed Nuuanu flows indicate that they were probably extruded during the Kaena (95-foot) stand of the sea (Stearns and Vaksvik, 1935, p. 113). No additional evidence has been developed either from the test borings or from the field studies of Wentworth and of Winchell for the Board of Water Supply.

Pali.—The famous Nuuanu Pali road across the Koolau mountain ridge provides good exposures of the Pali volcanics. Gairdner (1835) was apparently the first to describe volcanic cinders at the locality. Dana (1849, p. 260) recognized the unconformity between the cinders and the underlying Koolau basalts. Hitchcock (1900, p. 36) deduced the geologic history with only slight errors.

The Pali eruption (Pl. 1) may have covered the entire 1000-foot fluted cliff (the *Pali*) at this point, filling the steep (70°–80°) valleys and mantling the ridges between. Erosion has since uncovered many of the ridges, and, because the already partly weathered Koolau basalt was more easily eroded, the modern valleys in the cliff have been developed where the ridges once were. Lithic tuff underlying the cinders and agglomerate in places shows that steam blasts preceded the main part of the eruption. A deposit of breccia located in the walls of the theater-headed valley near the tip of the main mass of the Pali eruptive rocks, containing blocks as large as 3 feet across, suggests that the head of the valley coincides in part with the explosion crater. Stearns and Vaksvik (1935, p. 117) dated the Pali eruption in late Kaena (95-foot stand) time by the following reasoning, tentatively accepted: Pali volcanic rocks lie over Kaneohe, Nuuanu, and Aliamanu deposits, but under tuff from Salt Lake Crater. Pali cinders are interbedded with alluvium in terraces probably graded to the Kaena stand of the sea. They therefore originated during the latter part of that stand.

The Pali flow and its presumed dike feeder are composed of olivine, plagioclase, nepheline, pyroxene, ores, and minor amounts of biotite and apatite. Some of the olivine is visibly zoned, with core of lower birefringence and rim of higher birefringence. Occasionally there is a narrow zone of iddingsite between. If completely separated by iddingsite, the inner and outer zones of olivine may have the same or different orientations; otherwise, the zones have parallel orientation.

Makawao.—A breccia filling a ventlike structure near Makawao Stream (Pl. 1) was described by Stearns and Vaksvik (1935, p. 118). They assigned the breccia to an eruption during Kaena time but did not indicate any alkalic affinity of the tuffaceous rock which is composed of numerous feldspar crystals in a matrix of brown glass of indefinite composition. No nepheline or melilite was reported. Petrographically such a rock seems more closely allied with adjacent tuff beds of the Koolau series than with any of the alkalic Honolulu series products, since the latter all contain at least traces of nepheline, melilite, or other similar minerals. Since the breccia is largely confined to the volcanic pipe, its age is difficult or impossible to determine.

Kaau.—On a Koolau spur that separates the upper portion of Palolo Valley into two major sections known as Waiomao and Pukele valleys, Kaau Crater (Pl. 1) is a saucer-shaped swampy area about half a mile in diameter, with steep, almost circular walls of Koolau basalt. Thick tuff deposits near the crater, and very

thick alluvial tuffs in Palolo Valley show that phreatic explosions took place during the activity at this crater. The present topography is the result of slumpting, as shown by the comparatively fresh Koolau basalt cropping out in the walls of the crater and by the alluvial deposits in the bottom. Nepheline-melilite basalt ledges occur on the south rim at an elevation of 1700 feet, 100 feet above the present drainage outlet into Waiomao Stream. The lava lake overflowed at least once into Waimao Valley on the east, and probably into two branches of Pukele Valley on the south and west, sending three or more flows down into the Palolo drainage area by these routes.

A line of diamond-drill holes put down by the Board of Water Supply across the middle section of Palolo Valley has been described by Wentworth (1938, Figs. 59, 60). Further study of the cores confirmed his conclusions. A tuffaceous bed lies at considerable depth in Palolo Valley, suggesting a very early explosive eruption of Kaau Crater, followed by a quiescent period with perhaps minor activity. A much later large explosion preceded two lava flows separated by a minor explosion. Then the Kaau lava lake drained away, and collapse of the rim exposed Koolau flows in all the walls.

The earliest eruption was not mentioned by Stearns and Vaksvik (1935, p. 123–127). They dated Kaau Crater in pre-Waipio time on the basis of exposures of nepheline basalt without melilite in Kapahulu quarry. Wentworth (1938, p. 57–60) showed that Hole 20 drilled in the grounds of Liliuokalani School passes through nepheline basalt like that at the quarry, but at an elevation of 125 feet, or 50 feet higher than the highest elevation that could reasonably have been attained by Kaau basalt in the vicinity. The Kaau flow contains much melilite. The Kapahulu quarry rock therefore should not be correlated with lava of Kaau Crater, but rather with that of Mauumae Crater.

Reliable means of dating the Kaau eruptions are lacking. Tuffaceous alluvium indirectly originating at Kaau Crater extends down Palolo Valley almost to the coastal plain, but its relations to the sediments are obscured by the Kaimuki-Mauumae complex at the mouth of the valley. As suggested by Wentworth, the Kaau eruptions possibly took place much earlier than Laie time. This is probably the case for the earliest eruption which poured out the lowest flow in the bottom of the Palolo Valley fill; but the latest flows may have been as recent as Kaena or Laie time.

Mauumae.—Dana (1849, p. 242) described Mauumae cone as a cinder-scoria pile marking the location of a former vent. The cone is composed of pyroclastic material and only a few trickles of lava, but it is the source of the flow exposed in Kapahulu quarry. The flow was encountered in Hole 20 (Winchell, H., lab. notes W-4, Spec. W-2221; B. W.-S. lab. notes, Spec. 920; B. W.-S., 1937, p. 143). Mauumae cone has been erroneously described as a source of ordinary basalt (Cross, 1915, p. 19; Wentworth, 1926, p. 92; Stearns and Vaksvik, 1935, p. 140), and correctly described as a source of melilite-nepheline basalt (Powers, 1920, p. 273). Wentworth later modified his original conclusion (1938, p. 60) and stated that the cone did erupt nepheline basalt, his original specimen having come from a ledge of Koolau rock which crops out under the eastern slope of the cone. Stearns (1940, p. 52) agreed with Wentworth's new interpretation.

The Mauumae nepheline basalt and associated pyroclastics are tentatively correlated with the Laie (70-foot) stand of the sea because no appreciable unconformity can be found between them and the Kaimuki and Diamond Head rocks of Waipio age; some of the Kapahulu quarry rock shows a pillow structure suggesting submarine movement of the lava. The rock therefore belongs to the last high stand of the sea preceding the subaerial Kaimuki and Diamond Head eruptions.

WAIPIO (−60-FOOT) STAND OF THE SEA

General statement.—Several Honolulu series eruptions took place during the Waipio stand of the sea. These eruptions cannot be compared with one another as to age, except locally where structural relations demonstrate the relative age of two or more.

Salt Lake (Aliapaakai) and Makalapa craters.—The Salt Lake tuff formation is a subaerial deposit on the dissected surface of a Kaena terrace cut in Aliamanu tuff (Pl. 1). It contains a zone of upright tree molds extending below sea level. The Salt Lake and Makalapa tuffs are indistinguishable. They were first ascribed to the Waipio (−60-foot) stand of the sea by Stearns and Vaksvik (1935, p. 127–129).

No lava flows have been found associated with the Salt Lake and Makalapa tuffs. Wentworth (1926, p. 105) reported melilite in two specimens of tuff, with nepheline and labradorite in one of them; he reported no feldspar in a third specimen and mentioned none of these minerals in his description of a fourth. Cross (1915, p. 23) included one of the craters about Salt Lake and Makalapa among the sources of nepheline basalt. Powers (1920, p. 273) also cited two of the Salt Lake craters as sources of nepheline basalt. The author found neither nepheline nor melilite in any specimen of Salt Lake or Makalapa tuff; but, lacking lava or its equivalent, one would not be justified in denying that these minerals might result if the magma could be allowed to crystallize.

Olivine-rich bombs occur in the Salt Lake tuff. Some are almost entirely olivine (dunite). Some contain augite (peridotite). Ore minerals occur mostly along the intergrain boundaries, but partly included in the olivine (rarely zonally) and to some extent in the pyroxene. A black augite, pale green in thin section, is the variety commonly present; it forms also individual crystal lapilli in the tuff. Pyroxene with strongly developed parting appears in some bombs, usually associated with red garnet. This pyroxene is a pale-green diallage with approximately the same refractive indices as the augite. Other bombs contain a deep olive-green mineral tentatively identified as hastingsite. The minerals from these bombs are listed below with their refractive indices.

Mineral	N_X	N_Y	N_Z
Olivine	1.662	1.70	1.710
Pyroxene			
Augite lapilli	1.669	1.680	1.701
Diallage (green)	1.669	1.681	1.701
Hastingsite	1.662	1.677	1.688
(Hastingsite*)	1.663	1.677	1.685
Garnet			
Red		1.753	
Brown		1.805	

* Larsen and Berman, 1934, p. 224, No. 41.

The formula given by Larsen and Berman for their hastingsite is $Na_2Ca_4(Mg, Fe)_8(Al, Fe)_6Si_{12}O_{44}(OH)_4$, with Mg:Fe = 1.7:1 and Al:Fe = 2.1:1. The brown garnet may be a titaniferous variety, as suggested by its high index and high dispersion; the red is probably pyrope-almandite.

Ainoni, Castle, Maunawili, and Training School.—These four centers of eruption are located in the windward foothills of the Koolau Range within a circle 3½ miles in diameter (Pl. 1). Their mutual age relations have not been determined, except that they all probably belong to the Waipio (−60-foot) stand of the sea. Ainoni and Maunawili lavas are definitely post-Kaena, as Stearns and Vaksvik (1935, p. 131) show by means of outcrops where the flows cover sediments graded to the Kaena stand of the sea. The similar age, the close proximity, and the petrographic similarity of Ainoni, Maunawili, Training School, and Castle lavas suggest that they represent nearly simultaneous eruptions from the same magma reservoir.

The Ainoni flow is composed of nepheline basalt containing brown-rimmed olivine and zoned augite phenocrysts. In some, a remarkably prominent hourglass structure is developed. A small amount of analcime is present in some phases of the lava. Nepheline, pyroxene, ore minerals, and a few grains of apatite form the groundmass. This description applies equally well to the Maunawili, Training School, and Castle lava flows; melilite is locally present in the Training School (and the Castle?) flow. An analysis and further discussion of the Training School flow will be found below.

The Training School eruption can be ascribed definitely to the time of the Waipio (−60-foot) stand of the sea, since the flow rests unconformably upon a sandstone and conglomerate terrace graded to the Kaena (95-foot) stand and was cliffed by the sea during the Waimanalo (25-foot) stand. Whether it is older than the Maunawili and Ainoni flows (Stearns and Vaksvik, 1935, p. 132) as suggested by differences in the underlying unconformities, or of the same age as suggested by lithologic and spatial similarities, cannot be determined.

The Castle cinders and lava flow are on the north slope of Ulumawao Peak, west of Kailua. Little is known of their age relations. The flow apparently was cliffed by the sea in Waimanalo time. Its advanced state of weathering suggests great age as soil mantles most of the surface. Only lithologic evidence and approximate age identity support the correlation of this vent with the Training School, the Ainoni, and the Maunawili ones.

Diamond Head, Kaimuki, and Black Point.—The tuff cone Diamond Head (Pl. 1) is a famous landmark at the southeast end of Waikiki Beach. Two to 6 feet of this tuff lies above Mauumae lava in Kapahulu quarry. The top of the tuff is baked at the contact with the overlying Kaimuki lava. The apparent conformity between the tuff and the Kaimuki lava suggests that very little time elapsed between the Diamond Head and Kaimuki eruptions. The tuff also lies under Black Point lava with approximately the same relation of baked, columnar-jointed, relatively unweathered tuff in conformable contact with the bottom of the basalt.

No lavas are known to have originated from Diamond Head; however, the Kaimuki and Black Point lavas may represent late phases of the Diamond Head eruption. Wentworth (1926, p. 104, Spec. 15, 23) found nepheline in one, and probably in two, out of three specimens of Diamond Head tuff. Powers (1920, p. 273) related

the tuff to nepheline basanite magma from a dike which was exposed through the reef a few feet offshore near Black Point. The dike is now less prominent than formerly (*e.g.*, Hitchcock, 1900, p. 45). Diamond Head must have erupted during the Waipio (−60-foot) stand of the sea, because all visible tuff is subaerial in structure; but there are pebbles of the tuff in a limestone deposit due to the Waimanalo (25-foot) stand of the sea (Stearns and Vaksvik, 1935, p. 137).

Kaimuki Crater tops a low lava dome (Pl. 1) between Mauumae and Diamond Head craters. The lava of this dome probably came from the same fissure as the tuff of Diamond Head and the lava of Black Point. Dana (1849, p. 242) described the craters Kaimuki, Diamond Head, and Mauumae, concluding that, "As Diamond Hill and these two craters are upon the same line, they may have originated in the opening of a single fissure, and have been contemporaneous in their ejections." The relation of Diamond Head and Kaimuki to Mauumae has been proved otherwise.

The low eminence of Black Point on the southeast side of Diamond Head rests on calcareous reef rock partly covered by Diamond Head tuff. The Black Point and Kaimuki lavas are composed of olivine, plagioclase, pyroxene, magnetite, and a little nepheline and analcime. They are therefore nepheline basanites.

Kamanaiki.—A flow of nepheline-melilite basalt from a vent presumably near the triangulation station Kamanaiki, on the summit of the southeast wall of Kalihi Valley, forms the bed of Kamanaiki Stream for more than 1000 feet (Pl. 1). It ends at a 100-foot fall where 40 feet of Kamanaiki lava is exposed filling a V-shaped valley in Koolau lava flows. A patch of similar lava on the southeast slope of Kalihi Valley opposite this flow lies too high to be a part of the Kalihi volcanics and differs from Kalihi lava in containing no dunite nodules. The two lava flows appear to have originated in the same fissure and have been named Kamanaiki basalt by Stearns and Vaksvik (1935, p. 143). No evidence of volcanic activity was found at the summit of the ridge, and probably the two flows originated at different outcrops of a common dike feeder, rather than at a common source above. The Kalihi and Haiku vents are in a direct line with these two outcrops of the fissure and may form a continuation of it.

A wide apron of nepheline-melilite basalt underlying the coastal plain in the Kalihi-kai district of Honolulu is correlated lithologically with the Kamanaiki flow. Its age is indicated by the local stratigraphy, which includes soil, 5 or more feet of lava, Waimanalo (25-foot sea) reef rock, and a little modern alluvial soil. The reef rock shows that the Kamanaiki flow was emplaced before the Waimanalo stand of the sea, and the underlying soil shows a subaerial emplacement; the Waipio (−60-foot) stand of the sea is therefore indicated.

Punchbowl.—Punchbowl tuff cone is a prominent landmark near the center of Honolulu (Pl. 1). It consists mainly of palagonite tuff but includes a small amount of black cinders and spatter and some lava. A few outcrops of nepheline basalt occur in the crater, and a massive flow at least 15 feet thick was exposed in 1940 during excavations for the Beretania office building of the Board of Water Supply. The lava flow may have originated at dikes that are said to crop out at several places around the outer slopes of the crater, including the site of the reservoir on the south slope (Hitchcock, 1900, p. 43). Punchbowl is not so deeply gullied as Diamond

Head, although it is now in an area of greater rainfall. Stearns and Vaksvik (1935, p. 148) showed that the eruption took place during the Waipio (−60-foot) stand of the sea. Possibly it may be related to the Kamanaiki eruption because the vents lie on a line and are lithologically and temporally similar. However, they are several miles apart.

WAIMANALO (25-FOOT) STAND OF THE SEA

No known eruptions took place during Waimanalo time.

KAPAPA (?) (5-FOOT) AND MODERN (0-FOOT) STANDS OF THE SEA

General statement.—Two groups of eruptions have been dated with the most recent stand(s) of the sea. If there was a stand at 5 feet (Kapapa), the Koko eruptions probably took place then, and the Tantalus eruptions either then or later. Both eruptions were very recent, irrespective of the evidence for a Kapapa stand.

Koko group.—From a fissure that extended from Koko Head to Manana (Rabbit) Island along the southeastern extremity of Oahu (Pl. 1), a group of eruptions issued probably almost simultaneously and died out first at Manana Island and last at or near Koko Head. A similar space-time distribution was developed in the 1940 eruption of Mauna Loa, Hawaii Island, which started with activity along a 2½-mile rift and then, weakening after the initial outburst, ceased first at the south and then progressively northward along the crack. Evidence for a sequence along the Koko rift is scanty, but where any is available the northerly vents appear to have ceased action first. Thus Manana tuff occurs along the windward cliffs of the Koolau pali, but not on the Kaupo flow which issued therefrom. No relation is known between the windward and the leeward vents. However, Koko Crater tuff overlies the pyroclastics of Kalama Crater, and angular unconformities (Pl. 2, fig. 2) at Hanauma Bay indicate a complex history of the south end of the fissure. Lava flowed down Kalama Valley until it was deflected by a previously formed mound now a part of Koko Crater. Thus, Koko Crater erupted before as well as after Kalama Crater.

Vents of the Koko fissure are related to the same magma—nepheline basanite carrying much feldspar and rather little feldspathoid. The rarity of feldspathoid requires that the rock be classified as an alkali basalt or linosaite (Johannsen, 1938, p. 68). Wentworth (1926, p. 107) described a certain mineral as occurring in "euhedral lath-shaped crystals" in the Manana Island tuff. Melilite ordinarily occurs in plates rather than laths in the Honolulu series lavas; but a random section of such a plate might appear lath-shaped. Melilite was not found in this or any other part of the Koko fissure products, although several thin sections were searched carefully for it.

The tuff formations of Koko Crater provide ample opportunity for the study of interesting minor stratigraphic details. Mantle bedding (Pl. 2, fig. 2), bomb sags (Pl. 2, fig. 1), aerial cross bedding, and lustrous black augite crystal lapilli warrant special mention. Hourglass zoning is strongly developed in most of the crystal lapilli.

Tantalus group.—The group of craters centered about the head of Makiki Valley

in Honolulu includes at least five identifiable vents. This cluster of craters is called the Tantalus group from the name of the triangulation station on the rim of the highest crater (Pl. 1). The cones are composed of mantle-bedded black ash and lava balls, piled to a depth of several tens of feet. The same cinders extend as mantle-bedded deposits over the Koolau basaltic, and the coastal-plain sedimentary terranes from the Tantalus apex leeward 3½ miles to the coast. The black ash frequently forms valley walls of remarkable steepness and height.

Melilite-nepheline basalt lavas poured southwestward down Pauoa Valley north of Tantalus and cascaded eastward down the steep west wall of Manoa Valley, spreading out over the broad valley floor and pushing Manoa Stream far to the east against the Koolau bedrock wall of the valley. The latter flow is known as the Sugar Loaf flow from the popular name of Puu Kakea cinder cone near its source. A small flow broke out from a dike feeder now exposed in Kanealole branch of Makiki Stream at an elevation of about 1500 feet. This flow and dike have not been recorded previously in the literature. The flow moved down a channel older than the present one, which is cut in cinders that once buried the outcrops. The present channel does not coincide exactly with the older one but crosses it several times and tends to follow the edge of the flow.

Petrographically, the Pauoa flow is unusual for its high percentage of melilite plates, sections of which are elongate, giving the rock a felty appearance in thin section. Flow textures are developed locally. Parts of the Sugar Loaf flow have similar felty and fluidal textures. These flows are both characterized by few augite and olivine phenocrysts, variable proportions of melilite phenocrysts, and a groundmass composed of much pyroxene, melilite, and nepheline, and a rather large amount of ore minerals.

STRUCTURE

Dana (1849, p. 12) noted that the islands of the Pacific Ocean are arranged in lines or belts of various lengths and widths. The Hawaiian Islands represent a narrow belt of volcanic vents about 2000 miles long and less than 100 miles wide (Fig. 1). Dana thought he could identify two parallel lines of major vents in the southeast "high" islands of the group. Several transverse rifts may also be postulated, as the lines Kauai-Niihau-Kaula, Haleakala-Kahoolawe, and others.

In individual major vents such as Haleakala, Maui Island, the central vent often lies at the intersection of three rift lines ideally meeting at about 120° (Fig. 2). Such rift lines are secondary to the great rift cited above as the locus of all the great vents of the Islands. The secondary rifts are generally marked by lava vents and cinder cones on the younger islands, or by great concentrations of dikes on islands where erosion has progressed to a depth of a few hundred feet below the original surface.

The Koolau Range is the remnant of the once very elongate Koolau dome. In this dome the three ideal rift lines corresponding to those just described for Haleakala may be identified as follows: (1) the east rift, extending from the crateral region of the Koolau volcano (now marked by the Kailua crater-filling series) toward, and

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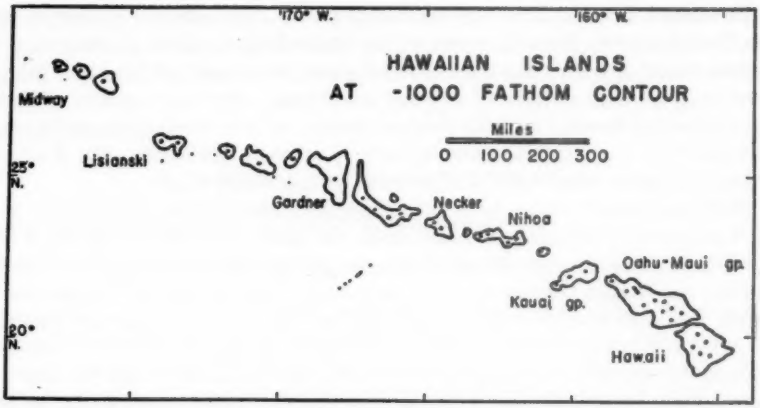

FIGURE 1.—*Hawaiian Archipelago at the 1000-fathom submarine contour*
Dots indicate known or presumed volcanic vents. U. S. C. G. S., Chart 4000, 1938.

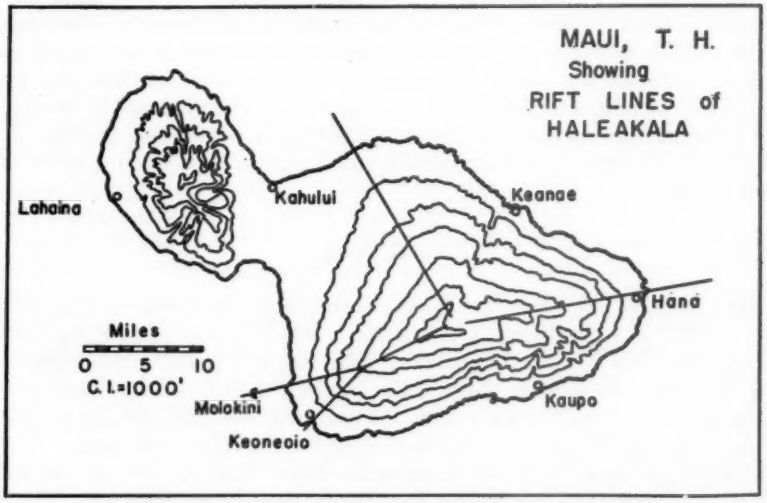

FIGURE 2.—*Principal rift lines of Haleakala volcano, Maui Island*

just north of the southeast tip of Oahu; (2) the overdeveloped northwest rift, extending from the same center northwest along the entire length of the Koolau Range to Kahuku Point, the northern tip of the island; and (3) an underdeveloped south rift which extends from the same center southward toward Diamond Head. The Koolau rifts were not developed so ideally as those of Haleakala; the northwest rift was strongly overdeveloped and became a great ridge, while the south rift was developed so little that its structural importance has not been previously recognized.

The hydrologic effects of concentrations of dikes in the vicinity of Kaau Crater and seaward along the east and west walls of Palolo Valley toward Mauumae, Kaimuki, and Diamond Head craters were discussed by Wentworth (1938, p. 41a–49a). In this area "dike subcomplexes" which are supposed to strike at right angles to the

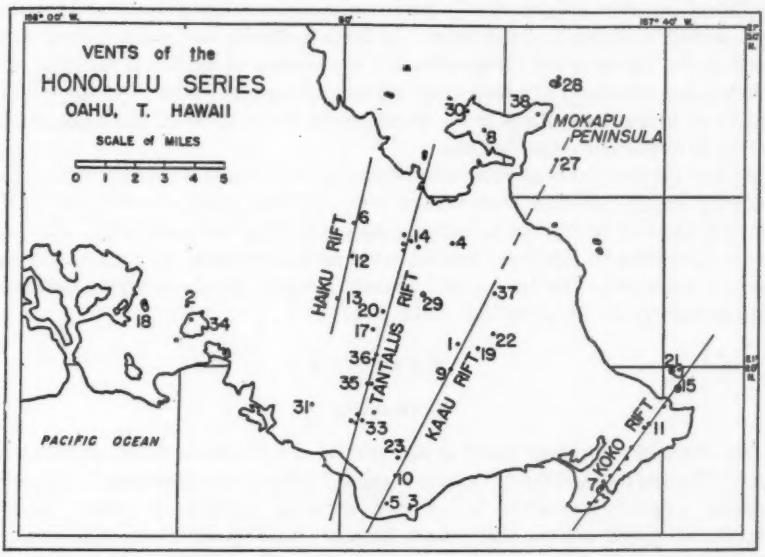

FIGURE 3.—*Probable rift lines controlling eruptions of the Honolulu series*

main Koolau dike complex were mentioned by Wentworth and Jones (1940, p. 982), but their great structural significance was not seen. Several large dikes, as the Palolo dike (Palolo boss of Stearns and Vaksvik, 1935), have been generally recognized; and bosslike "buds" in the same region are believed to be the uppermost widened portions of dikes that reached, or almost reached, the original surface of the Koolau dome (Wentworth and Jones, 1940, p. 988). In the light of Wentworth's mapping and some further field reconnaissance, the author proposes that these dikes and subcomplexes represent the otherwise missing south rift zone of the Koolau volcano. This identification is partially confirmed by the fact that no other such concentrations of dikes have been found in the leeward slopes of the Koolau Range.

The author's interpretation of the rift system of the Honolulu series is illustrated in Figure 3, which is based primarily on field evidence and secondarily upon petrographic and geographic (map) evidence. Certain rift lines are undoubtedly valid, as the Koko and Kaau lines; for convenience in tabulations certain other geographic groups of vents are placed together without necessarily implying genetic relationship. Table 3 shows the rift groups, the related groups, and the geographic but not neces-

sarily related groups of vents and gives the mineral composition of a representative specimen from each.

The following conclusions may be drawn from a study of Table 3. (1) All lavas of the Koko rift contain a large proportion of feldspar, a little feldspathoid, olivine, and much pyroxene. (2) The lavas of the Kaau rift vary most widely, four at the south end containing feldspar; only one contains much melilite; all show feldspathoid and abundant olivine and pyroxene. (3) Both nepheline and melilite occur in the lavas of the Tantalus and Haiku rifts, but the amount of melilite is variable; other minerals are essentially common to all the lavas of these two rifts. (4) Alteration of olivine to iddingsite appears to be characteristic of the lavas of the Kaau rift and occurs in only a few other localities.

Analysis of the known age relations of the vents of the series is not very informative. Activity seems to migrate from west to east, and from north to south; this is true not only from rift to rift, but also among the vents of the individual rifts. However, many exceptions to this trend appear, and conclusions based on such scanty data are not warranted. Tables 1 and 2 contain the data for the analysis; details are recorded elsewhere (Winchell, H., 1941, p. 134).

MINERALOGY

FELDSPAR

No orthoclase has been found in any rock of the Honolulu series, and it is very rare in Koolau rocks, although a little is usually indicated in the norm. Any potash feldspar present is occult—*i.e.*, hidden in solid solution in other minerals. Macdonald (1942) showed that potash feldspar probably occurs in solid solution in plagioclase, producing anomalous optical properties. Such feldspar occurs in Koolau lavas and may occur in exceedingly rare cases in the Honolulu lavas.

Some rocks of the Honolulu series contain plagioclase with composition ranging from sodic bytownite to sodic labradorite. Plagioclase phenocrysts are rare; if present, they are often zoned. Zoning is usually from calcic labradorite cores to sodic labradorite margins, with rare local reversals; the variation in anorthite content is less than 10 molecular per cent. These data are based on extinction angles determined in thin sections of known orientation and were confirmed in a few instances by refractive-index determinations.

The groundmass plagioclase in specimens of the Honolulu series consists of a felty network of intermediate to sodic labradorite laths of about the same composition as the typical outer zones of the phenocrysts. Interstitial plagioclase occurs in only a few specimens. Its composition is a trifle more sodic than that of the laths and may include potash feldspar. The material is very fine-grained and impossible to determine accurately.

OLIVINE

All lavas of the Honolulu series contain at least some olivine, usually as phenocrysts, as do many of the pyroclastic rocks. Under certain conditions of wave

TABLE 3.—*Mineral and rift relationships**

	←Phenocrysts→				←Groundmass→														
	Labradorite	Augite	Olivine	Iddingsite	Melilite	Ores	Pyroxene	Labradorite	Nepheline	Analcime	Perofskite	Apatite	Hastingsite	Glass	Palagonite	Calcite	Zeolite	Pegmatoid	Xenoliths (Dunite etc.)
KOKO RIFT																			
Manana tuff	?	x	x	?	[a]	x	...	...	...	...	...	...	...	x	?	x	x	...	....
Kaohikaipu lava	[b]	...	x	...	...	x	x	?	x	...	...	x	...	x	...	...	...	...	....
Kaupo flow	...	...	15	...	...	5	50	30	?	...	...	x	...	...	...	...	...	...	....
Kalama flow	...	x	10	...	...	7	30	40	6	7	...	x	...	x	...	...	...	x	....
Koko Crater tuff	...	x	x	...	...	...	...	...	...	...	...	...	...	x	x	x	...	...	....
Kahauloa tuff	...	x	x	...	...	...	...	...	...	...	...	...	...	x	x	x	...	...	....
Koko dike flow	...	?	5	...	...	5	35	50	x	3	...	1	...	...	...	x	x	...	....
Hanauma Bay tuff	...	x	x	...	...	...	...	...	...	...	...	...	...	x	x	x	...	...	....
Koko Head tuff	...	x	x	...	...	...	...	...	...	...	...	...	...	x	x	x	...	...	....
KAAU RIFT																			
Training School	...	x	12	...	3	8	32	...	35	...	...	x	?	10	...	...	...	x	....
Maunawili	...	20	5	x	...	8	50	...	20	...	[e]	x	...	...	...	...	...	x	....
Ainoni	...	1	9	x	...	x	x	...	x	?	...	x	...	x	...	...	...	...	....
Kaau	...	10	10	...	20	5	25	...	30	x	[e]	x	...	...	...	x	x	x	....
Mauumae	...	15	10	x	...	5	35	...	25	...	x	x	x	...	...	...	...	x	....
Kaimuki	2	5	5	x	...	5	30	50	x	?	...	...	...	?	...	...	...	...	....
Black Point	...	x	20	x	...	6	40	30	3	3	...	...	...	...	...	x	...	...	....
Diamond Head tuff	...	...	x	...	...	x	...	...	...	...	...	...	...	x	x	x	...	...	....
Dike	...	...	10	...	...	5	60	15	5	2	...	...	...	x	...	...	1	...	....
TANTALUS RIFT																			
Kaneohe	...	2	10	...	20	3	30	...	35	...	...	x	...	x	...	...	...	...	....
Makuku, Nuuanu	...	20	15	x	x	5	30	...	25	?	...	x	...	...	...	...	...	x	....
Luakaha, Nuuanu	...	2	10	x	x	5	40	...	30	?	...	x	...	...	...	...	...	x	x
Tantalus (Pauoa)	...	...	5	...	35	3	30	...	25	...	...	x	...	...	...	2	...	...	....
Sugar Loaf	...	5	15	...	30	2	25	...	35	1	[d]	x	...	...	...	...	x	x	....
Rocky Hill	...	10	15	...	[c]	x	30	...	35	...	...	x	...	7	...	...	...	...	....
HAIKU RIFT																			
Haiku (2 vents)	...	15	20	...	[f]	5	25	...	25	x	x	x	...	x	...	...	x	[g]	....
Kalihi	...	1	16	?	18	9	30	[h]	23	3	...	x	[h]	...	...	[h]	[h]	[h]	[h]
Kamanaiki	...	?	15	...	25	5	20	...	20	...	...	x	...	15	...	...	...	...	....
(Punchbowl?)	...	10	15	...	...	3	25	...	45	...	...	x	x	1	x	x	...	...	....
SALT LAKE GROUP																			
Aliamanu tuff	...	?	x	...	...	x	...	...	x	...	...	...	...	x	x	x	x	...	....
Salt Lake tuff	...	x	x	...	...	x	...	...	x	...	...	...	...	x	x	x	x	...	[i]
Makalapa tuff	...	x	x	...	...	x	...	...	x	...	...	...	...	x	x	x	x	...	....

*Quantities are estimated volume percentages.

TABLE 3.—*Concluded*

	←Phenocrysts→						←Groundmass→											
	Labradorite	Augite	Olivine	Iddingsite	Melilite	Ores	Pyroxene	Labradorite	Nepheline	Analcime	Perofskite	Apatite	Hastingsite	Glass	Palagonite	Calcite	Zeolite	Pegmatoid	Xenoliths (Dunite, etc.)
HAWAIILOA GROUP																			
Pali Kilo	...	12	10	?	...	3	50	...	25	...	...	...	...	...	...	...	...	...	....
Hawaiiloa	...	1	20	...	20	6	20	...	30	x	...	x	x	x	...	x	x	[j]	x
Mokolea	...	5	13	...	20	6	20	...	30	...	...	x	...	x	...	...	...	...	....
Moku Manu	...	7	13	x	...	5	35	...	40	...	...	x	...	x	...	...	...	x	....
Ulupau Head tuff	...	?	x	x	...	x	...	...	...	...	...	...	...	x	x	x	?	...	x
Ulupau lava (dike?)	...	5	x	x	...	5	45	...	25	...	...	?	...	...	...	...	...	...	....
OTHERS																			
Castle	...	10	15	x	...	5	35	...	35	...	...	x	...	...	...	...	...	...	....
Pali	...	...	20	x	...	5	50	15	5	...	...	x	...	x	...	...	...	...	[k]

[a] Reported by Wentworth (1926, p. 107) with query (?).
[b] Bytownite.
[c] Reported by Stearns and Vaksvik (1935, p. 190–191).
[d] Found in specimen W-245; reported by Moehle (1902, p. 83) and Merrill (1900); Cohen (1880, p. 56) found a mineral he called picotite.
[e] Melilite abundant in some specimens, lacking in others.
[f] Melilite abundant in pegmatoid specimens.
[g] Pegmatoid specimen W-106 contains 20 per cent melilite, 5 per cent analcime, little pyroxene, and traces of biotite, chlorite, glass, perofskite, and zeolite. Normal lava contains up to 40 per cent pyroxene including zoned augite phenocrysts.
[h] Variable.
[i] Eclogite, dunite, and peridotite bombs.
[j] Secondary quartz and phillipsite in cavities.
[k] Dunite and peridotite; green spinel or garnet reported by Stearns and Vaksvik (1935, p. 189, Spec. F-63).
x Positively identified.

erosion, placer deposits have been concentrated at the beach line. Several typical specimens of olivine are listed in Table 4. The composition ranges from 12 to 20 molecular per cent fayalite for olivine associated with the Honolulu series. Olivine occurring in the Koolau series contains less iron.

Table 3 shows that about a third of the 41 vents listed produced olivine with appreciable alteration to iddingsite. Some olivine shows this alteration in peripheral zones, but other grains have it in a zone near but not at the margin. In the latter, the marginal zone usually has a different composition from the core, and it may have the same or a different orientation as illustrated in Figure 4. Resorption of olivine is apparent in specimens of both Honolulu and Koolau lavas.

PYROXENE

Pyroxene crystallizes through a long period under variable conditions. Augite phenocrysts in the Honolulu series are always zoned, often in patterns resembling an hourglass. There may be noticeable relief and a difference of birefringence between the core and the periphery in such phenocrysts. A number of specimens are described below:

W-348. Augite crystal lapilli from Kahaloa, Koko group, consist of shining black crystals with sharp edges and clean faces. Some form aggregates of twins and simple crystals. Twins are partly skew cruciform penetration twins and partly arrowhead shapes due to contact twinning on (100). $N_X = 1.695$, $N_Y = 1.700$, $N_Z = 1.718$; $2V = 55°$; $Z:c = 43°$ to $50°$ in different zones, with marked

TABLE 4.—*Optical properties of Honolulu series olivine*

	N_X	N_Y	N_Z	2V	Fo:Fa (mol.)
W-362. Crystal lapilli from Tantalus black ash. Tabular on 010.	1.677	1.688	1.710	−84°	80:20
W-402. Phenocrysts from Pali lava 1250 feet above sea level in channel passing road jct. Tabular on 010. Zoned: c for core, r for rim.	1.680 (c) $B_r - B_c = 0.0013$*			90°	86:14 (c) 79:21 (r)
W-467. Peridotite and eclogite bombs, Salt Lake Crater. Granular, equant, anhedral.	1.660	1.673	1.690	+85°	88:12

* Thin-section determination of differential birefringence depends very little upon the thickness of the section, is therefore of higher order of accuracy than determination of birefringence itself, provided that the latter is known approximately, and that the orientation is the same for both parts of the grain.

dispersion r less than v; the following crystal forms are found: {100}, {010}, {110}, {$\bar{1}$11}, {$\bar{2}$21}, {021}, and ?{001}.

W-468. Augite crystal lapilli from Salt Lake Crater consist of dirty, broken, dull, somewhat altered crystals. Some crystal forms are recognizable. $N_X = 1.698$, $N_Y = 1.710$, $N_Z = 1.729$. The extinction angle varies about 5° from zone to zone.

W-467. Diallage from garnetiferous bomb, Salt Lake Crater, is anhedral to subhedral and occurs mostly in crumbling bombs with several kinds of garnet, olivine, and ore minerals. Twin striae or inclusions produce a banded structure in thin sections. $N_X = 1.669$, $N_Y = 1.680$, $N_Z = 1.701$.

F-368. Augite phenocryst from Moku Manu, in thin section loaned by H. T. Stearns. Hourglass structure is clearly visible because of relief and color in plane-polarized light. Between crossed nicols zoning is clearly visible because of variation of birefringence and extinction angles ($Z:c = 45°$–$51°$ in different zones).

In the groundmass of most Honolulu series lavas the pyroxene is slightly brownish and therefore easily distinguishable from olivine and melilite. This color may indicate the presence of titanium. Optical properties show that groundmass pyroxene is pigeonite, richer in iron than the augite phenocrysts.

ORE MINERALS

The term *ore minerals* is used in this paper to indicate all black opaque minerals with metallic luster. Separation of the component from powdered specimens is easily accomplished with a magnet. Its composition, as indicated by the analyses of the rocks, includes considerable titanium, probably as ilmenite. The latter is distinguishable from magnetite in some cases by means of its crystal habit. Magnetite tends to be equant, octahedral; ilmenite, to be elongated. The norms of the analyzed rocks include from 7 to 12 per cent total ores by weight, generally with more magnetite than ilmenite. Modally, the ores are usually estimated at

about 5 per cent by volume; even the most careful micrometric determinations may be unreliable because the average diameter of ore grains is often less than the thickness of the sections.

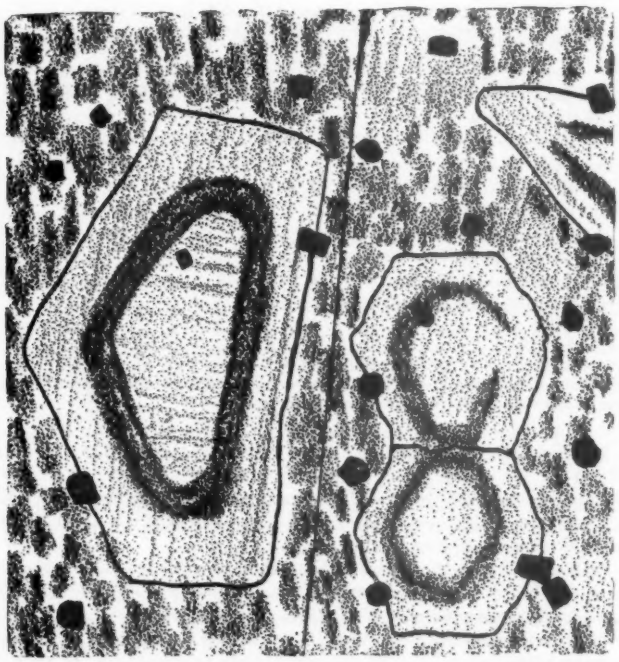

FIGURE 4.—*Olivine phenocrysts sketched from a thin section of Pali lava*

Olivine cores are surrounded more or less completely by zones of iddingsite, and outside the iddingsite another generation of olivine was formed. The two generations of olivine may have the same or different orientations. Section W-409.

MELILITE

Platy melilite, about three to five times broader than thick, is abundant in many Honolulu series lavas and pyroclastic rocks. It occurs as small phenocrysts in the glassy fragments which constitute the black ash of the Tantalus eruptions. In lavas from the same source, melilite tablets are much larger and show slight zoning, usually made visible by differential birefringence. The evidence strongly indicates that melilite crystallized both before and after eruption. "Peg structure," due to inclusions of low refringence, low birefringence, and parallel extinction, is typical of many but not all melilite grains. The basal cleavage or parting is usually represented by a single crack in about the middle of each grain. The refractive indices, $N_O = 1.661$, $N_E = 1.655$, indicate a composition close to 75 molecular per cent gehlenite, 25 per cent akermanite; if zoned, the periphery has slightly higher

akermanite content. Abnormal interference colors are never found in melilite from the Honolulu series.

NEPHELINE

The mineral most characteristic of the Honolulu series is nepheline. Almost all the lavas are either nepheline basalts or nepheline basanites. In the nepheline basalts, the mineral forms 15 to 50 per cent of the rock volume. No zoning has been detected in any specimens, even with a sensitive staining procedure. Sections normal to the optic axis are often roughly hexagonal in outline, but other evidences of euhedral growth of nepheline crystals are lacking. The mineral is one of the last to crystallize. It sometimes forms large oikocrysts enclosing fine-grained pyroxene and rounded ore minerals.

For micrometric purposes staining with methyl blue has been very successful in helping to distinguish nepheline (dark blue) from melilite (light blue) and other minerals including feldspar. Glass and weathering products gelatinize and absorb the stain but can be distinguished by the greenish color resulting from the combination of the blue stain and the yellow, brown, or other color of the mineral. After staining, analcime is very difficult to distinguish from nepheline, but it is not abundant and can easily be identified in the unstained portions of the thin sections. Even after staining, the birefringence of nepheline sometimes distinguishes it from analcime.

An excellent technique for staining thin sections was described by Shand (1939, p. 508–510). It is unnecessary to use an entire thin section, and indeed it is often convenient to retain about half of each section in balsam without stain by simply scratching the cover glass and uncovering only half the slide for staining.

ACCESSORY AND PEGMATOID MINERALS

General statement.—Wherever quarrying operations have exposed large areas in the interior of nepheline or nepheline-melilite basalts, pegmatoid segregations have been found. Pegmatoid veins with zeolitic minerals in what were once open spaces were brought up by the diamond drill from several places in the Nuuanu and Mauumae flows.

The paragenesis of the pegmatoid minerals at Moiliili quarry has been described by Dunham (1933; 1935). His paragenetic table does not show crystallization of augite belonging to the phenocryst phase, nor the early crystallization of ore grains found included in olivine phenocrysts; it shows no perofskite. The paragenesis of the minerals at the Hawaiiloa quarry in the Naval Reservation is practically the same as that of Moiliili quarry except for the absence of hydronepheline and allophane and the presence of some secondary quartz incrustations.

Analcime.—Small amounts of analcime are present in many of the Honolulu lavas. It is considered a feldspathoid in classifying the linosaite and basanite obtained from the Koko and Kaimuki regions. It occurs mainly in pegmatoid segregations, but it has not been found in all segregations studied. The Kalihi nepheline-melilite basalt probably contains more analcime than any other lava flow on Oahu, but the amount does not justify naming the rock a nepheline-analcime basalt (Stearns

and Vaksvik, 1935, p. 192, Spec. F-135). The lava contains at least as much melilite, although pegmatoid segregations contain abundant analcime. The subordinate quantity of analcime might be clarified by naming the lava "analcime-bearing nepheline-melilite basalt."

TABLE 5.—*Paragenetic list of minerals in pegmatoid segregations at Moiliili and Hawaiiloa*

		Moiliili (Dunham, 1933)	Hawaiiloa (Spec. W-439 to 441)
PYROGENE	Chiefly magmatic	Olivine Augite Nepheline Melilite Ore	Olivine Augite Nepheline Melilite Ore
	Chiefly deuteric	Perofskite* Apatite	Apatite Hastingsite Analcime
SECONDARY	Metacolloid	Allophane	
	Zeolitic	Chabazite Phillipsite Hydronepheline Calcite	Chabazite Phillipsite Quartz Calcite

* Perofskite found in Specimen W-245; not reported by Dunham.

Apatite.—The most widespread accessory mineral is apatite. At least a few tiny acicular prisms, often less than 0.05 mm long, can be found in almost every thin section. Pegmatoid zones often contain up to 3 per cent of apatite in large, acicular crystals which penetrate nearly all the other minerals, especially nepheline and analcime. Large fluor-apatite crystals may be 3 mm long and 0.2 mm in diameter.

Hauynite.—The Sugar Loaf flow contains rare, small, euhedral, pinkish grains of hauynite. This mineral was reported after a study of a lava ball originating at the Round Top or the Sugar Loaf vent (Stearns and Vaksvik, 1935, p. 189, Spec. F-35). The author found hauynite in thin sections of three different specimens from the same vicinity, including a lava ball and two specimens of the Sugar Loaf flow at Manoa Road below the vent. The index of refraction is about 1.498. Crystal form, color, and refractive index identify the mineral.

Perofskite.—Honolulu lavas contain rare traces of perofskite. However, one thin section of a specimen of the Haiku flow contains about 1 per cent of this mineral by volume. It has been reported or found as shown in Table 6.

Chlorite.—Specimen W-106, representing an outcrop of the Haiku lava flow at the stream junction noted above, contains a few flakes of a greenish pleochroic mineral of low birefringence and moderate relief which were tentatively identified as chlorite. This is the only known occurrence of chlorite in the Honolulu series.

Biotite.—Specimen W-106 also contains several flakes of a brown mineral of moderately high relief and birefringence. An interference figure was obtained from one flake, and its identification as biotite is considered certain. The mineral has been found at other places as follows: Moku Manu (Stearns and Vaksvik, 1935, p. 195, Spec. F-368); periodotite bombs from Aliamanu Crater (Wentworth, 1926, p. 111).

Garnet.—Two types of garnet have been found in olivine eclogite bombs collected at Salt Lake Crater. Specimen W-467 contains a red garnet with N = 1.753. Its color and isotropism suggest that it belongs to the pyrope-almandite-spessartite system, with a composition of about 40 per cent almandite, 60 per cent pyrope, and possibly some grossularite (Winchell, A. N., 1933, p. 176). A

brown garnet (N = 1.805) was found in thin section W-467.2. The material is also isotropic, suggesting affinity with the same system. If so, its composition should be near 80 per cent almandite, 20 per cent pyrope, and probably a little andradite; however, its color and high index of refraction may indicate the presence of a titanium-bearing component. Garnet was first found at Salt Lake Crater by Hitchcock (1900, p. 38).

TABLE 6.—*Perofskite in the Honolulu series*

Formation and locality	Reference
Sugar Loaf flow at Moiliili quarry	Spec. W-245. Reported by Moehle (1902, p. 83) and Merrill (1900). Cohen (1880, p. 56) found a mineral he called picotite, which may have been perofskite.
Kaau flow in Waiomao Valley	Stearns and Vaksvik (1935, p. 191, Spec. F-83).
Maunawili flow	Stearns and Vaksvik (1935, p. 190, Spec. F-64).
Mauumae flow (Hole 20, B. W.-S.)	Spec. 2221.7 at 159.5 feet.
Haiku flow below stream junction at 319 feet elevation.	Spec. W-106.

SECONDARY MINERALS

General statement.—Minerals due to weathering are not considered here. The pegmatoid minerals are secondary, but because of their evident pyrogenic origin they were considered in the preceding section. Zeolites, calcite, and quartz are classed as secondary minerals.

Zeolites.—Chabazite and phillipsite occur in pegmatoid zones in the Hawaiiloa and Sugar Loaf flows where quarries have exposed the interior of the rock. Their crystallization postdates that of all other minerals except calcite, quartz, and hydronepheline.

Calcite.—The most important secondary mineral, calcite, occurs in cavities in the rocks and was presumably deposited by ground waters. It forms the cementing matrix of most tuffs and of such zones of the black ash deposits as are in any way cemented. The Kalihi lava flow and the Kalihi branch of the Kamanaiki flow show large areas where single calcite crystals have grown through interconnecting interstices of the rock. Thin sections of such rocks present a "poikilitic texture" in the purely descriptive sense of the term. (Connotations regarding origin have no meaning in this case.) The calcite "oikocrysts" are frequently larger than an inch in diameter and may constitute as much as 15 per cent of the volume of the rock.

Quartz.—The last mineral except calcite to form in druses in the Hawaiiloa flow was quartz. This mineral has not been found in any other Honolulu series lavas; its association in this case is probably fortuitous, since similar druses are common in parts of the Kailua (upper Koolau) series near Olomana Peak. Chalcedony amygdules occur in weathered Koolau dike complex near the Pali lava flow, but there also the relation appears to be accidental.

PETROGRAPHY

KOOLAU SERIES

Megascopically and microscopically the Koolau lava flows show a remarkable uniformity from top to bottom of the exposed stratigraphic section of the Koolau

dome, and from end to end. Random variations do occur, but the range of variation between adjacent flows is as great as that between widely separated ones. Eleven analyses of Koolau basalts have been collected by Wentworth and Winchell (1946, Table 4). Their average is given in Column A and is repeated here in Column A, Table 10. The Koolau basalts cover a relatively narrow petrographic range with variations mainly dependent upon the amount and kind of phenocrysts. Compared with basalts from other parts of the Hawaiian Islands, the Koolau series is remarkable for its high content of hypersthene, usually as phenocrysts that appear texturally equivalent to olivine. Feldspar and/or olivine phenocrysts may be present in addition to, or instead of, hypersthene. These phenocrysts are enclosed in a groundmass composed of pigeonite, feldspar, ore minerals (magnetite and ilmenite), sometimes hypersthene, sometimes olivine, and usually a few tiny crystals of apatite per thin section. The textures vary from glassy through intersertal to intergranular, and occasionally felty.

Chemically, the Koolau lavas have appreciably more silica than most Hawaiian basalts. This is shown by the presence of quartz in the norms of nearly all the analyzed Koolau basalts, contrasted with 1 to 10 per cent of normative olivine in various averages (Wentworth and Winchell, 1946, Table 5, Columns B, C, D, G) representing possible compositions of the "primitive" Hawaiian magma. The relative amount of silica may be expressed by a number that is positive and equal to the amount of normative quartz, or negative and equal to the amount of additional silica needed to just saturate all the normative molecules (0.43 forsterite plus 0.29 fayalite, or 0.40 olivine; 0.845 nepheline; 0.275 leucite; and so on). Larsen (1938, p. 516) used this number in constructing triangular diagrams representing six quantities derived from the norms. The silica saturation for the average of 29 analyses of basalts from Hawaii Island is −1.7 (Wentworth and Winchell, 1946, Table 5, Column C); that for the average of the 11 Koolau analyses is +2.40 (Column A). If the average of 49 analyses of olivine basalt is used (Column H) for an approximate analysis of the "primitive" Hawaiian magma, the silica saturation is −2.87.

HONOLULU SERIES

General statement.—In contrast to the very uniform Koolau basalts, the Honolulu series includes rocks ranging from linosaite and nepheline basanite to nepheline basalt and melilite-nepheline melabasalt. No representatives of this series have been found in the range of compositions with much nepheline and a little feldspar (nephelinite basanite). Linosaite and nepheline basanite (Johannsen, 1938, p. 68, 231) are represented by members of the series with feldspathoid content close to 5 per cent. Accurate quantitative determination of the amount of feldspathoid has been found impracticable because of the extremely fine grain sizes in such rocks. Whenever more than a few grains of nepheline were found in a thin section, it was assumed that the quantity was over 5 per cent, and the rock was therefore classed as nepheline basanite.

Linosaite and basanite.—Nepheline cannot be positively identified in the flows of the Koko group, but small grains of interstitial analcime and a few doubtful ones of nepheline warrant classification of the rocks as linosaite or alkali basalt. The

association of these rocks with the others of the Honolulu series which are certainly alkalic would justify this conclusion (Johannsen, 1938, p. 68).

The Pali lava probably contains the highest percentage of nepheline in a feldspar-bearing rock, although the exact amount is doubtful because of the fine grain size and weathered condition of the flow. Nepheline probably does not exceed 15 per cent of the volume.

Three rocks in the linosaite-basanite range have been analyzed. Detailed data on the localities where these and other specimens were collected for analyses will be found elsewhere (Winchell, H., 1941, Appendix).

Results of the linosaite-basanite analyses are shown in Columns 12 to 14 of Table 7 (Spec. 9962, 9982, 10402) with their respective norms, modes, and saturation numbers. The Koko dike flow, Column 12, is the only linosaite. Its analysis seems unusual with respect to the alumina and magnesia content, especially when compared with that of the Kalama flow, Column 14, which issued from the same rift feeder at approximately the same time. Mr. Gonyer repeated the necessary determinations and confirmed the original analyses. The normative olivine of Specimen 9962 (Column 12) is 29 molecular per cent fayalite, although the modal olivine is near the center of the chrysolite range as defined by Deer and Wager (1939, p. 25). Otherwise the norm and mode agree with a high percentage of light-colored minerals, rather high ore minerals, and about average pyroxene.

Nepheline basanite (Spec. 10402, Column 14) from the Kalama Crater flow was analyzed as a check on possible chemical variation in the Koko magma. Modally it differs from Specimen 9962 in containing more recognizable nepheline and analcime, less feldspar, and more pyroxene and olivine. The analysis and the norm reflect this condition accurately. In estimating the mode, the amount of light minerals in the groundmass of 9962 was set somewhat higher than Rosiwal measurements indicated because the high relief of the pyroxene tends to obscure small grains of feldspathic minerals.

The remaining analyzed feldspathic lava of the Honolulu series is the nepheline basanite of Black Point (Spec. 9982, Column 13). This basanite may be taken as a good representative of the feldspar-bearing members of the Honolulu series. Its composition, norm, and mode place it between the Koko linosaite and the nepheline basalts of the rest of the series. Nepheline constitutes nearly 10 per cent of the rock by volume. Staining of thin sections of this flow does not always distinguish between traces of almost colorless glass and the nepheline which is one of its essential constituents. The rocks of Black Point, of a dike near by (Cross, 1915, p. 23; Hitchcock, 1900, p. 45; and others), and of the Kaimuki lava dome appear similar in thin section.

Nepheline and nepheline-melilite basalt and melabasalt.—The most abundant lava types of the Honolulu series are nepheline and nepheline-melilite basalts. Six reliable analyses of such lavas are shown in Columns 15 to 20 of Table 7. Two more, probably less accurate because made on ignited material and apparently contaminated with copper from reagent or vessels, were reported originally by Lyons (1896, p. 424) and quoted by Cross (1915, p. 48, Nos. 36, 37).

Norms of rocks as low in silica as these do not agree obviously with their modes,

TABLE 7.—*Analyses, norms, and modes of Honolulu basalts*

	(12) 9962	(13) 9982	(14) 10402	(15) 9961	(16) 10399	(17) 10400	(18) 9960	(19)	(20) 10401	(A)	(B)
ANALYSES—WEIGHT PER CENT											
SiO_2	45.13	42.86	43.94	38.57	36.72	37.10	36.75	36.34	37.22	43.98	37.12
TiO_2	2.94	2.94	2.32	2.79	2.82	2.90	2.41	2.87	2.02	2.73	2.64
Al_2O_3	[a]16.40	11.46	12.60	11.71	11.56	11.12	11.98	10.14	12.08	13.49	11.43
Fe_2O_3	3.42	3.34	3.84	5.21	4.94	6.53	6.05	6.53	5.18	3.53	5.74
FeO	8.17	9.03	9.18	7.78	8.17	7.31	7.45	10.66	7.88	8.79	8.19
MnO	.07	.13	.09	.11	.13	.09	.08	.20	.11	.10	.12
MgO	[a]5.52	13.61	11.43	13.08	13.27	12.81	12.08	10.68	12.71	10.19	12.44
CaO	11.30	11.24	10.78	12.84	14.34	13.56	13.81	13.10	13.34	11.11	13.50
Na_2O	3.62	3.02	3.84	4.22	3.93	4.56	4.75	4.54	5.12	3.49	4.52
K_2O	1.02	.93	1.02	1.20	.62	1.20	.91	1.78	.71	.99	1.07
H_2O-	.42	.12	.02	.19	.41	.04	.36	1.00	.23	.19	.37
H_2O+	1.16	.44	.36	.59	1.63	1.11	1.61	1.00	1.73	.65	1.28
CO_2	.05	none	none	.27	none	none	none	.15	none	.02	.07
P_2O_5	.66	.52	.43	1.11	.82	1.19	1.41	1.02	1.40	.54	1.16
SO_3	.17	.22	.21	.17	.31	.34	.17	.10	.17	.20	.21
BaO	.06	.04	.08	.08	.11	.13	.13	n.d.	.12	.06	.11
SrO	none	none	none	none	none	none	none	n.d.	none	none	none
Cr_2O_3	none	.04	none	.06	.07	.04	.03	n.d.	.03	.01	.05
Sum	100.11	99.94	100.14	99.98	99.85	100.03	99.98	100.11	100.05	100.07	100.02
NORMS—WEIGHT PER CENT											
or	6.12	5.56	6.12							6.12	
ab	19.91	5.76	8.91							11.53	
an	25.58	15.29	15.01	9.45	13.07	7.23	8.90	2.78	8.06	18.63	8.62
lc				5.67	3.05	5.67	4.36	8.28	3.49		4.80
ne	5.68	10.51	11.93	19.31	16.76	19.88	21.58	19.88	23.00	8.80	19.88
wo (di)	10.67	15.43	14.85	14.15	10.09	12.41	11.14	11.60	10.90	13.69	11.83
en (di)	6.50	11.10	10.10	10.80	7.60	9.90	8.60	7.80	8.00	9.20	8.90
fs (di)	3.56	2.90	3.56	1.85	1.45	1.06	1.32	2.90	1.85	3.43	1.72
fo (ol)	5.04	16.10	12.88	15.12	17.78	15.40	13.86	13.02	16.66	11.34	15.54
fa (ol)	3.06	4.69	5.10	2.86	4.08	1.84	4.49	5.30	4.08	4.28	3.47
cs				3.44	8.77	7.05	7.40	8.00	7.05		6.88
mt	4.87	4.87	5.57	7.66	7.19	9.51	8.82	9.51	7.42	5.10	8.35
il	5.62	5.62	4.41	5.32	5.32	5.47	4.56	5.47	3.80	5.17	5.02
ap	1.68	1.34	1.01	2.69	2.02	2.69	3.36	2.35	3.36	1.34	2.69
Sum	98.29	99.17	99.45	98.32	97.18	98.11	98.39	96.89	97.67	98.63	97.70
th	b	b	.43	b	.57	.57	b		.28	.43	
cc	.08			.60				.32			
Sat'n	−7.98	−17.16	−17.16	−26.58	−26.94	−27.96	−29.28	−29.34	−31.26	−13.50	−28.20
MODES—VOLUME PER CENT[d]											
Augite[e]	tr		tr	2	tr	tr	1	d 5	tr		
Olivine[e]		15	5	15	10	12	16	15	20		
Feldspar	50[f]	30[g]	40								
Melilite				5	20	3[h]	18	20	20		
Magnetite[i]	5	6	7	7	5	8	9	5	6		
Olivine[j]	2	40	5	34	55	32	30	29	tr 20		
Pyroxene	35[f]		30								
Nepheline	tr	6	6			35[k]	23	25	30		
Analcime	2		7	36[m]	tr		3		tr		
Glass		2	tr			10			tr		
Apatite	1	tr	tr	1	tr	tr		1	tr		
Zeolite	tr	1			10				3		
Calcite	tr	tr							1		

TABLE 7—*Continued*

[a] A chemical check of these values by Mr. Gonyer confirmed them.
[b] .002 mol. SO_3 neglected.
[c] Visual estimates indicating order of magnitude (½ to 1½ times the amount shown).
[d] Specimen W-244, from quarry described by Cross; not necessarily from the same portion as his analyzed specimen.
[e] Phenocrysts.
[f] Very fine-grained groundmass; feldspar-pyroxene ratio not accurately determinable. Estimates of feldspar vary from less than 30 to about 50 per cent; latter is preferred because of high felsic content indicated by analysis.
[g] Probably nepheline in part. Fine grain of groundmass makes distinction locally impracticable.
[h] Locally variable. Low because part of melilite is included with nepheline.
[i] Includes ilmenite.
[j] Groundmass.
[k] Including part of melilite.
[m] 36 per cent observed gelatinized material in stained section. Analcime not noted.

(12) Honolulu linosaite from southwest edge of flow in gulch north of Hanauma Bay, Koko Head. Elevation about 130 feet. Long. 157° 41′ 38″ W., Lat. 21° 16′ 33″ N. Dark-gray, vesicular, practically nonporphyritic basaltic rock. Gonyer, analyst. B. W.-S. field no. 9962.

(13) Honolulu nepheline basanite from south tip of Black Point (Kupikipikio), near foot of steps on public right-of-way from shore to Black Point Road. Long. 157° 47′ 45″ W., Lat. 21° 15′ 30″ N. Very dark-gray (nearly black), vesicular basaltic rock with inconspicuous olivine phenocrysts. Gonyer, analyst. B. W.-S. field no. 9982.

(14) Honolulu nepheline basanite from Kalama Crater flow at road cut on east side of Kamehameha highway between Koko Crater and Makapuu Head. Long. 157° 39′ 52″ W., Lat. 21° 17′ 54″ N. Medium-gray, somewhat vesicular, very fine-grained basaltic rock with few phenocrysts. Gonyer, analyst. B. W.-S. field no. 10402.

(15) Honolulu nepheline basalt from lower Nuuanu (Luakaha) flow, northwest bank of Nuuanu Stream above Kapena Pool. Long. 157° 50′ 50″ W., Lat. 21° 19′ 43″ N. Very dark-gray, fine-grained, crystalline basaltic rock with 2-mm olivine phenocrysts scattered sparsely throughout. Almost no vesicles. Gonyer, analyst. B. W.-S. field no. 9961.

(16) Honolulu nepheline-melilite basalt from Kaau lava flow on east side of Waiomao Road, 250 feet from north end. Long. 157° 47′ 3″ W., Lat. 21° 18′ 53″ N. Medium-gray, practically nonvesicular rock with inconspicuous olivine phenocrysts. Gonyer, analyst. B. W.-S. field no. 10399.

(17) Honolulu nepheline basalt from prominent outcrop of Training School flow in orchard east of Kamehameha highway, 0.3 mile southwest of Kailua junction. Long. 157° 45′ 40″ W., Lat. 21° 22′ 55″ N. Medium-gray, practically nonvesicular, crystalline basaltic rock with 2–4-mm. olivine phenocrysts which are conspicuous because of their light-green color and large size. Gonyer, analyst. B. W.-S. field no. 10400.

(18) Honolulu nepheline-melilite basalt from Kalihi flow in Kalihi stream channel at Water Reserve boundary. Elevation 600 feet. Long. 157° 50′ 10″ W., Lat. 21° 22′ 12″ N. Specimen for analysis consisted of chips of 2-inch diameter or smaller, hand-picked to eliminate olivine segregations (dunite) common in this flow. Dark-gray, massive basaltic rock with megascopically visible grains. Besides the dunite nodules, some olivine phenocrysts may be identified in hand specimen. Such grains were not removed in sorting. Gonyer, analyst. B. W.-S. field no. 9960.

(19) Honolulu "nephelite-melilite basalt, Moiliili quarry, Oahu" (Cross, 1915, p. 22). Known as Sugar Loaf flow (Stearns and Vaksvik, 1935). Long. 157° 49′ W., Lat. 21° 17′ N. Cross' analysis reported .04 S; transcribed here as .10 SO_3. Cross' description: "Megascopically a gray massive trap of millimeter grain, the holocrystalline character of which is suggested by numerous glistening crystal or cleavage faces of unrecognizable minerals. The hand lens reveals a large amount of light-colored minerals. No phenocrysts can be observed. There are some small, irregular cavities lined with a thin, zeolitic crust. The constituents are olivine, augite, melilite, nephelite, magnetite, and apatite, all but the apatite being abundant. All the minerals are very fresh, and the absence of iron hydroxide makes recognition of almost every particle possible."

Much of the rock at Moiliili quarry is similar to this, but of half or quarter the grain size mentioned by Cross. Steiger, analyst.

(20) Honolulu nepheline-melilite basalt from flow north of Puu Hawaiiloa, Mokapu Peninsula. Large block from newly opened (1940) quarry in naval reservation. Long. 157° 45′ 25″ W., Lat. 21° 27′ 25″ N. at the quarry. Slightly vesicular, gray rock with few olivine phenocrysts. Grain size less than 1 mm, but boundaries and crystal or cleavage faces are distinct under hand lens. Gonyer, analyst. B. W.-S. field no. 10401.

(A) Average of columns (12)–(14), inclusive.
(B) Average of columns (15)–(20), inclusive.

as do norms of the less basic rocks. Modal melilite contains calcium which is calculated as calcium orthosilicate (*cs*) in the norm. Aluminum and magnesium in the melilite are calculated with anorthite and olivine in the norm, giving these minerals a slight excess in comparison with the mode. Other elements in melilite do not so seriously affect the norm because of their relatively small amounts. If proper allowance is made for these facts, the norms will be seen to correspond remarkably well with the modes.

The lower Nuuanu (Luakaha) nepheline basalt (Table 7, Spec. 9961, Column 15) has slightly higher magnesia than other analyzed specimens of the Honolulu series. Modally, however, it does not differ significantly from them, and its separation would not be justified on chemical grounds alone. The norm and mode agree tolerably well.

The Training School lava (Spec. 10400, Column 17) includes the second highest percentage of normative calcium orthosilicate in the entire group of analyzed Honolulu series specimens. Careful examination of stained thin sections shows that the groundmass takes up the stain in two different degrees of intensity—dark for nepheline and light for melilite. Pyroxene in the same rock sections takes up no stain. The best means for determining the modal percentage of pyroxene is to measure the amount of pyroxene plus melilite in unstained section and to subtract from the sum the amount of melilite determined in a stained portion of the same section. The silica saturation of this rock is about the same as that of the Luakaha (Column 15) and Kaau (Column 16) flows.

Kaau Crater lies 3 miles south of the Training School vent on the same rift line (Fig. 3; Pl. 1). Higher alumina and lower alkalies produce a marked increase in normative anorthite in the Kaau lava (Table 7, Spec. 10399, Column 16). The modal changes responsible for this difference are mainly variations in the amounts of pyroxene and melilite.

Nepheline-melilite basalts from Kaau, Kalihi, Sugar Loaf, and Hawaiiloa vents have similar compositions, norms, and modes (Columns 16, 18, 19, and 20). This constancy of products in different groups of vents of the Honolulu series suggests a similar differentiation process for all.

The Kalihi, Sugar Loaf (Moiliili quarry), and Hawaiiloa flows have much in common. The pegmatoid bodies common to all Honolulu series flows seem especially abundant in these three. Differing phases of the Kalihi flow such as dunite nodules, pegmatoid bodies, and calcite-rich areas were carefully sorted out of the sample submitted for analysis. The same procedure was followed in collecting the sample for analysis from the Hawaiiloa flow. Cross' sample from Moiliili quarry may have contained pegmatoid material since he refers to its "millimeter grain" (1915, p. 21). However, his photomicrograph and petrographic description are of normal, nonpegmatoid material.

Many rocks analogous to the Honolulu nepheline basanites, linosaites, and nepheline basalts have been analyzed. A few are quoted in Table 8. Specimen 9962 from the Koko dike flow near Hanauma Bay (Column A) corresponds excellently with the type rock of the alkali basalt group (Column B) named linosaite by Johannsen (1938, p. 68), and with the alkali melabasalt (Column C). The similarity of norms and saturation numbers is very striking for Columns A and B. The 1905–6 lava of Matavuna Volcano in Samoa (Column D) is intermediate between the linosaite (Column A) and the average of the nepheline basanites (Column E) of Oahu.

The analysis of nepheline basanite from Ciruella (Column F) probably does not correspond to the average of the Oahu basanites (Column E) so closely as others that might be found in the literature, but it demonstrates the affinity of the two rocks. Similarities may also be found between the Oahu basanites (Column E) and that of Scharfenstein (Column C).

TABLE 8.—*Composition of Hawaiian and related rocks, analogues of Honolulu basalts*

	(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)	(I)
ANALYSES—WEIGHT PER CENT									
SiO_2	45.13	46.55	42.75	43.76	43.40	42.35	37.12	37.50	38.74
TiO_2	2.94	3.84	2.13	3.41	2.63	1.82	2.64	3.21	3.30
Al_2O_3	16.40	14.55	17.24	11.58	12.03	12.29	11.43	9.12	11.30
Fe_2O_3	3.42	3.17	8.10	4.39	3.59	3.89	5.74	5.59	4.28
FeO	8.17	7.88	5.88	7.57	9.10	7.05	8.19	8.81	7.71
MnO	.07	.10			.11	.21	.12	.15	n. d.
MgO	5.52	8.61	6.17	12.97	12.52	13.09	12.44	13.72	11.97
CaO	11.30	8.75	11.14	9.64	11.01	12.49	13.50	13.85	14.43
Na_2O	3.62	3.71	4.21	3.03	3.43	2.74	4.52	2.69	3.02
K_2O	1.02	1.62	2.48	1.84	.98	1.04	1.07	.63	1.92
H_2O-	.42	.03	1.06		.07	.32	.37	1.05	.60
H_2O+	1.16	.14		.47	.40	1.50	1.28	2.35	1.28
CO_2	.05	none		.38	none		.07	.27	
P_2O_5	.66	.55	tr	.45	.48	.99	1.16	.90	1.77
SO_3	.17			.14	.22	.05	.21	[a]tr	
BaO	.06				.06	.10	.11	.07	
SrO	none				none	.09	none	.05	
Cr_2O_3	none				.02	.10	.05	.07	
Others		[b].12		[c].15		[c].07		[d].16	
Sum	100.11	99.62	101.16	99.78	100.05	100.19	100.02	100.19	100.32
NORMS—WEIGHT PER CENT (NEGLECTING py, th, cc IF PRESENT)									
or	6.12	9.45	14.5	11.12	5.56	6.12			
ab	19.91	23.32	.5	10.48	7.86	3.93			
an	25.58	18.35	20.9	12.51	15.57	18.35	8.62	11.12	12.23
lc							4.80	2.62	8.72
ne	5.68	4.40	19.0	8.24	10.51	10.08	19.88	12.21	13.63
di	20.73	17.05	27.1	23.65	28.85	29.55	22.45	31.90	27.67
ol	8.10	13.53	2.5	18.27	19.46	18.41	19.01	18.28	15.64
cs							6.88	3.61	4.05
mt	4.87	4.64	11.8	6.50	5.34	5.57	8.35	8.12	6.26
il	5.62	7.30	4.2	6.54	5.02	3.50	5.02	6.08	6.23
ap	1.68	1.34		1.01	1.01	2.35	2.69	2.02	4.03
Sat'n	−8.0	−9.1	−17.1	−13.4	−16.6	−15.9	−28.2	−19.6	−21.6

[a] Reported "S, trace."
[b] NiO, .12.
[c] ZrO_2, none; V_2O_3, .04; (Ni, Co)O, .03; Li_2O, trace; S, trace.
[d] Cl, .05; ZrO_2, .02; V_2O_3, .05; NiO, .04.
[e] S, .15.

(A) Linosaite, Koko dike flow near Hanauma Bay, Oahu, T. H. (Analysis 12, Table 7, Spec. 9962).

(B) Linosaite, Il Fosso, Linosa, Italy. Analyst Washington (Washington, 1908).

(C) Unnamed alkali melabasalt (melalinosaite?—H. W.), Scharfenstein, Mittelgebirge, Bohemia. Author Hibsch, from Washington (1903, p. 345).

(D) Nepheline basalt, 1905–6 lava from Matavuna Volcano, Savaii, Samoa. Analyst Heuseler, author Klautsch, from Washington (1917, p. 675). Norm recalculated.

(E) Average of analyses 13 and 14, Table 7.

(F) Nepheline basanite, Ciruella, Colfax Co., N. M. Analyst Hillebrand, author Cross, from Johannsen (1938, p. 235). Norm from Washington (1917, p. 677).

(G) Average of analyses 15–20, Table 7.

(H) Melilite-nepheline basalt, Kilauea Bay, Kauai, T. H. Analyst Hillebrand, author Cross (1915, p. 17). Norm from Washington (1917, p. 725).

(I) Ankaratrite, Tsiafajovona, Madagascar. Analyst Boiteau, author Lacroix, from Washington (1917, p. 725).

Nepheline-melilite basalts of the Honolulu series (Column G) do not correspond to many analyzed rocks. The melilite-nepheline basalt from Kauai (Column H) is close to the average of the related Oahu rocks. Its normative calcium orthosilicate and silica deficiency are lower than those of the Oahu rocks. The analogue from Madagascar (Column I) is like that from Kauai in having higher normative anorthite, slightly different calcium orthosilicate, and less silica deficiency. These seem to be the closest melilite and nepheline-melilite basalts that occur elsewhere and have chemical and mineralogical characteristics in common with the Oahu rocks. Analogous rocks having more potash and less soda are more numerous.

PETROGENESIS

SUMMARY OF THE DATA

Any hypothesis to account for the origin of the Honolulu series must take into account several outstanding facts; to be complete, it must also explain many minor features. The Honolulu series is confined geographically to a few small patches in southeastern Oahu and to a relatively narrow stratigraphic horizon representing only a small proportion of the total time interval near the end of the known geologic history of the island.

The high deficiency of silica in most of these lavas, compared with the slight excess in the lavas of the Koolau series, is very significant. All analyzed Honolulu series rocks have at least 5 per cent less silica than the least silicic Koolau rocks, and the maximum difference is nearly 15 per cent. The alumina percentage and the ferric-to-ferrous iron ratio are the most important points of difference after the silica.

DEFICIENCY OF SILICA

There is an excess of nearly every constituent except silica in the Honolulu series rocks over the corresponding constituent of the Koolau series. If the difference between them is due primarily to transfer of silica from Honolulu to Koolau magmas without appreciable change of other constituents, we should be able to prove it by adding or subtracting silica to each analysis until some arbitrary limit is reached where all analyses of Koolau and Honolulu rocks will be essentially alike. The origin of chalcedonic amygdules associated with Koolau dikes below the Nuuanu Pali pass, and of small quartz crystals in cavities in the dike complex near Kailua and in cavities in the Hawaiiloa flow, might conceivably be related to such a process.

For example, the various analyses may be modified by subtracting (algebraically) the silica saturation numbers from the silica percentages in the analyses, and recalculating to 100 per cent. Such a procedure gives analyses which have neither quartz nor olivine in the norms. Table 9 shows the results obtained in this manner, and Figure 5 is a variation diagram showing the resulting silica percentages as a function of the changes made. A modification of the procedure leading to a small negative saturation number instead of exactly zero would probably yield better equivalence of the silica percentages, but would have insignificant effects upon the

TABLE 9.—*Saturated equivalents of Koolau and Honolulu analyses (Calculated to 100 per cent after subtracting saturation numbers from silica percentages)*

	(1) 10404	(2)	(3) 10403	(4) 9991	(5)	(6) 10398	(7) 9986	(8) 10396	(9) 9980	(10) 11320
SiO_2	46.75	46.50	48.69	47.57	49.16	51.78	49.50	47.68	50.41	48.59
TiO_2	2.71	4.24	2.75	2.19	2.62	1.73	2.23	2.45	2.17	3.67
Al_2O_3	15.90	14.72	15.08	16.61	14.80	15.29	15.73	16.16	13.87	17.71
Fe_2O_3	3.73	10.30	2.99	3.76	2.90	3.22	2.28	4.19	2.41	5.03
FeO	7.18	2.79	8.66	8.21	8.75	7.54	8.38	7.25	7.69	6.48
MnO	.11	.71	.09	.12	.09	.05	.09	.06	.11	.06
MgO	7.05	6.53	7.68	7.05	7.06	6.94	7.83	7.05	10.28	4.07
CaO	10.59	10.23	9.84	10.42	10.85	8.25	9.81	10.02	8.59	8.68
Na_2O	2.75	3.52	2.68	2.48	2.75	3.93	2.75	2.80	2.58	4.11
K_2O	.23	.18	.37	.18	.31	.62	.11	.22	.62	.81
H_2O-	.20	n.d.	.13	.29	.06	.23	.27	.71	.08	.06
H_2O+	2.39	n.d.	.63	.78	.32	.64	.65	1.20	.62	.31
CO_2	none	n.d.	none	none	none	none	none	none	none	none
P_2O_5	.38	.28	.37	.13	.33	.69	.15	.08	.28	.36
SO_3	.03	n.d.	none	.15	n.d.	none	.17	.09	.22	.02
BaO	none	n.d.	none	none	n.d.	none	none	none	none	none
SrO	none	n.d.	none	none	n.d.	none	none	none	none	none
Cr_2O_3	none	n.d.	.04	.06	n.d.	none	.05	.04	.07	.04

	(11) 9948	(12) 9962	(13) 9982	(14) 10402	(15) 9961	(16) 10399	(17) 10400	(18) 9960	(19)	(20) 10401
SiO_2	51.00	49.10	51.28	52.09	51.46	50.20	50.83	51.00	50.72	52.54
TiO_2	1.47	2.72	2.51	1.98	2.20	2.22	2.27	1.86	2.22	1.53
Al_2O_3	12.36	15.17	9.60	10.73	9.27	9.11	8.69	9.26	7.84	9.13
Fe_2O_3	3.14	3.18	2.86	3.27	4.13	3.90	5.10	4.68	5.04	3.91
FeO	7.41	7.56	7.72	7.82	6.15	6.44	5.71	5.76	8.23	5.96
MnO	.09	.06	.11	.08	.09	.10	.07	.06	.15	.08
MgO	13.52	5.11	11.66	9.75	10.30	10.45	10.01	9.34	8.25	9.62
CaO	7.30	10.46	9.62	9.19	10.15	11.30	10.50	10.70	10.12	10.08
Na_2O	2.30	3.35	2.58	3.27	3.33	3.13	3.56	3.68	3.51	3.87
K_2O	.15	.95	.80	.87	.95	.49	.94	.70	1.38	.54
H_2O-	.33	.39	.10	.02	.15	.32	.03	.28	1.55	.18
H_2O+	.65	1.08	.38	.31	.47	1.30	.87	1.25		1.31
CO_2	none	.05	none	none	.21	none	none	none	.12	none
P_2O_5	.04	.61	.44	.37	.88	.65	.93	1.09	.79	1.01
SO_3	.05	.15	.20	.18	.15	.24	.27	.12	.08	.13
BaO	none	.06	.03	.07	.06	.09	.10	.10	n.d.	.09
SrO	none	none	none	none	none	none	none	none	n.d.	none
Cr_2O_3	.19	none	.03	none	.05	.06	.03	.02	n.d.	.02

(1)–(11) Koolau basalt (Wentworth and Winchell, 1946, Table 4).
(12) Honolulu limosaite (Table 7).
(13)–(14) Honolulu basanite (Table 7).
(15)–(20) Honolulu nepheline-melilite basalt (Table 7).

other constituents. In Table 9 all the components of Honolulu series rocks are closer to the corresponding components of Koolau rocks than before subtraction of the saturation numbers. Thus the total iron is now almost the same (although the ferric-

to-ferrous iron ratio remains different). Titania is almost the same across the table; magnesia is uniform with one exception; lime, soda, and potash are a little higher in the Honolulu than in the Koolau rocks. The minor constituents are a little higher except for the erratic chromic oxide. These small differences, together with the large

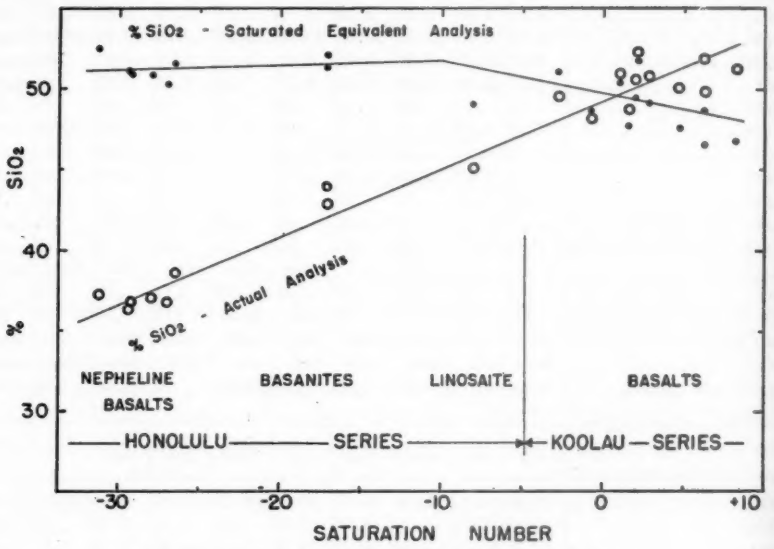

FIGURE 5.—*Variation diagram based upon silica saturation*

Showing the effect of adding or subtracting enough silica to eliminate all quartz and olivine from the calculated norm.

difference in alumina, show that desilication alone, of a basalt intermediate between the Honolulu and the Koolau basalts, is not sufficient to produce rocks like those of the Honolulu series. However, simple desilication is plainly an important part of the process, and the magma from which the Honolulu series was derived probably did not have exactly the composition postulated.

MINERALIZERS

Smyth (1913; 1927) has proposed that alkalic rocks are the result of very long, slow cooling without tectonic disturbance, in places sufficiently enclosed to keep the mineralizers trapped with the magma. The mineralizers so trapped act on the magma producing alkalic rocks by concentration of certain constituents, for example in the upper part of the magma chamber. The presence of large amounts of mineralizers is demonstrated in the Honolulu lavas by the abundant pegmatoid bodies described above and by the analyses of the lavas themselves. It is also suggested by the large size of the black ash deposits which indicate long-continued fountaining, a process that occurs by the rapid evolution of gases at the vent. Resurgent gases (mostly steam) commonly produce tuff, as at Kaau Crater (ground water) and Diamond

Head (sea water) rather than black ash. Few pegmatoid bodies occur in the Koolau lava flows, whereas many are found in the lavas of the Honolulu series.

The time sequence of eruptions in southeastern Oahu, with a long erosion interval between the extinction of the Koolau volcano and the eruptions of the Honolulu ones, appears to agree also with the requirements of Smyth's hypothesis. Smyth suggests that the mineralizers must permeate the magma, and with cooling and incipient crystallization they should tend to segregate in the upper portion of the chamber. They are active in concentrating alkalies and to some extent the alkaline earth elements, but they would hardly account for the large increase in alumina noted in the preceding section, and it must be assumed that desilication is accomplished either by the settling of silica-rich minerals at an early, liquid stage of the magma history or by some type of hydrothermal activity.

There are few published laboratory data on anything but dry melts. In the products from natural processes that go on below the Koolau mountains, we have found some evidence favoring the hypothesis; but the evidence can also be interpreted in terms of other hypotheses. Perhaps the importance of mineralizers is more in maintaining a low melting point in the residual magma than in actively accomplishing the desilication and other chemical changes observed. However attractive the hypothesis may be, it can hardly be said to be proved.

MULTIPLE SUBSTRATUM HYPOTHESIS

Kennedy (1933) postulated that the generally accepted universal, world-circling basaltic substratum is in reality two layers, each the parent of a distinct rock suite. These layers are an upper one composed of magma designated the tholeiitic magma type (basalt—andesite—rhyolite series of differentiates) and a lower one composed of magma designated the olivine basalt magma type (basalt—trachyandesite—trachyte—phonolite series). The two thus represent two potential parent magma types which are responsible for the calc-alkaline and alkalic series of basaltic differentiates. The conditions under which magma may form from either of these substrata are such that only the olivine basalt magma typed (parent of alkalic rocks) may form in regions of long-continued crustal stability such as the Pacific Ocean basin (Kennedy and Anderson, 1938, p. 34, 49–60). A third fundamental stratum, the granitic, does not extend beyond continental borders. In stable, nonorogenic areas such as the Pacific basin the hypothesis demands the presence of rocks of only the one suite. But it hardly makes provision for the radically different alkalic rocks of the Honolulu series—not, at least, without modifications making this a special case too limited in application for effective argument. Neither of the series postulated would normally include a nepheline-melilite basalt.

LIMESTONE SYNTEXIS

A third alternative for the origin of the alkalic Honolulu series is a phase of Daly's hypothesis of limestone syntexis (1910, p. 87–118; 1918, p. 107; Shand, 1930). This requires the assumptions that limestone or other calcareous formations are traversed by the magma in its ascent, that syntexis takes place, and that lime and car-

bon dioxide are added to the magma. The lime is believed to accomplish the desilication, and the carbonic acid, the alkali concentration. The presence of melilite shows mineralogically a high lime content of the magma, and chemical analyses confirm the inference. Evidence for a high gas content of the magma during eruption also favors the theory provided that the gas is an oxide of carbon. The high ferric-to-ferrous iron ratio might result from partial reduction of CO_2 to CO. Necessary assumptions are that limestone is present in depth; that the limestone is so located that the magma can gain access to it; and that given access thereto, syntexis will take place and the basaltic magma will form nepheline-melilite basalts and other types included in the Honolulu series.

The first assumption, that at least some calcareous deposits exist on part of the sea floor in these warm waters, cannot be doubted. However, the amount of *Globigerina* ooze is probably small at the 18,000-foot depth at which the Hawaiian Islands must have started forming, because the water at that depth would tend to redissolve most of the carbonate tests dropped by pelagic organisms before such tests could reach the bottom. It may be argued that during the formation and underwater growth of the volcanoes time would be available for the formation of coral reef on top of the lava domes or around their margins, or for the accumulation of some calcareous oozes at shallower depths on top of the growing volcanic domes. However, this does not seem reasonable in view of our present knowledge of the rates of dome growth and coral growth on other Hawaiian volcanoes. Neither of the active volcanoes, Mauna Loa and Kilauea, has any fringing coral reef, although some parts of their coast lines are rather old. Haleakala and Hualalai, long dormant volcanoes and perhaps now extinct, also have no fringing reef. Even Mauna Kea, whose last eruptions took place probably during Pleistocene glaciation of the summit area, has no known coral reef along its shore. Only the oldest domes, as Kauai, Oahu, West Maui, and Lanai, have reef-protected shores in any part. The evidence seems strong then that dome growth is too fast to permit the establishment of reef-building colonies on active or dormant volcanoes in the latitute of Hawaii. The necessary consequence is that no calcareous formations are likely to exist interbedded with the Koolau series or with any other basement complex. The field evidence is especially significant in this respect. In spite of the known wide range of sea-level changes (at least 2500 feet with respect to Oahu and some other Hawaiian islands—*cf.* Table 1), no calcareous deposits of any kind have ever been found interbedded with the lavas of the Koolau series, nor with any other basement series in Hawaii. Numerous deep wells have been drilled to points well below sea level in Koolau formations without a single authentic record of one passing through calcareous deposits interbedded with the basement Koolau series.

The second assumption necessary to the syntexis theory as applied to Hawaii is accessibility of limestone to the magma with which it is to react. If Honolulu series vents lie above sediments in every case, with calcareous material constituting at least part of the sediments, an important datum of evidence would be established, since in accordance with the preceding paragraph, it is evident that no accessibility would be possible as long as the Honolulu magma is confined to passages and chambers in the Koolau series. Four groups of vents of the Honolulu series are well out on the coastal plain of Oahu, having been erupted through calcareous sediments as proved either by

adjacent wells or by fragments of reef rock actually included in the associated tuffs. These four are (1) the Salt Lake Crater group, including Aliamanu; (2) the Diamond Head group; (3) most of the vents of the Koko group; and (4) the vents on or near Mokapu Peninsula. These groups include vents that broke out under water and vents that erupted subaerially. Of the four groups known to have been erupted through calcareous sediments and reef rocks, only one (Mokapu Peninsula) surely erupted nepheline or nepheline-melilite basalt! The nature of the magma that produced the Salt Lake Crater vents is not certainly known. The rock composing the Diamond Head group is nepheline basanite and its correlative pyroclastics; that which composes the Koko group is nepheline basanite and linosaite and their correlative pyroclastics. Thus some of the least alkalic rocks of the Honolulu series are the ones that surely have come in contact with limestone or calcareous sediments.

Conversely, it is also true that some of the most alkalic rocks of the Honolulu series —the nepheline basalts and the nepheline-melilite basalts—have had the least probability of access to calcareous sediments. It has been shown that limestone interbedded with Koolau flows is very unlikely (1) because none has ever been found in the known stratigraphic range of several thousand feet, and (2) inductively, because the dome growth was probably too fast to permit accumulation of calcareous deposits until long after the Koolau volcanic activity was ended. Furthermore, the Ainoni, Maunawili, Training School, and Castle vents are located in the Koolau dike complex where limestone, even if once deposited locally, would have been assimilated, digested, and "flushed out" by the Koolau magmas erupted at the vents of the growing Koolau dome, so that none can reasonably be assumed to have persisted through the Koolau period. No evidence of the former existence of such calcareous deposits has ever been found in the Koolau dike complex. Such deposits could hardly remain inert to the Koolau lavas and then strongly react with the Honolulu magmas which moved upward along essentially the same routes.

Cross was not aware of the evidence so afforded by the dike complex, but he did not believe limestone syntexis played any part in the origin of the nepheline basalts of Oahu or of the soda trachytes of the other islands. He saw clearly that deep limestone encountered in Oahu wells belongs with the coastal plain series associated with the long post-Koolau erosion interval and is not interbedded with the Koolau lavas. Cross (1915, p. 90) says,

> "I am not aware of any basis for the broad statement that limestones are generally associated with the older lavas of the archipelago, nor indeed that they occur in such association at any point. Coral rock is known on the south shore of Oahu at considerable depths and to some extent alternating with lavas and ash beds, but that these belong to the old lavas of the principal centers rather than to later eruptions is not demonstrated and is, indeed, questionable."

The third assumption—that syntexis would take place if given a chance—has not been proved in the instances where contact surely occurred. Thus many blocks and pebbles of undigested reef rock may be found in the tuffs of Salt Lake, Diamond Head, Koko Head, Manana Island, and Ulupau Head. Some are metamorphosed, but others are hardly altered. Thus all three assumptions connected with the hypothesis of limestone assimilation or syntexis are false in some or all cases where evidence is available.

CRYSTALLIZATION DIFFERENTIATION—I

A proposal of Bowen (1928, p. 234) to account for alkalic rocks depends upon the incongruent melting of orthoclase, producing leucite as one phase at a certain temperature. If part of the liquid magma is removed at this point, reaction between the leucite crystals and an appropriate residuum may produce orthoclase and nepheline. The obvious difficulty in applying this principle to the genesis of Oahu rocks is their remarkably low potash content. The ratio of potash to soda is 9:91 in Koolau basalts (Wentworth and Winchell, 1946, Table 4, Column A) and 19:81 in Honolulu nepheline-melilite basalts (Table 7, Column B). These ratios are both lower than that for the average of Cross' 43 analyses of Hawaiian rocks (26:74, Wentworth and Winchell, 1946, Table 5, Column B). Therefore the described mechanism seems unlikely to produce the Honolulu nepheline-melilite basalts or even the basanites or linosaite of the series.

CRYSTALLIZATION DIFFERENTIATION AD HOC—II

Crystallization of essentially dry melts similar in composition to olivine basalts, at ordinary pressures known in the laboratory, does not lead to nepheline basalts. A frankly *ad hoc* process of differentiation by crystallization is postulated instead, in the belief that better discussion will be stimulated if there is something concrete to discuss, however unlikely it may seem. We observe that nepheline basanite, and ultimately nepheline basalt, will result if hypersthene basalt (instead of olivine basalt) crystallizes out from the primitive Hawaiian magma. This might make the Honolulu series complementary to, rather than descended from, the Koolau series with which it is associated in space if not in time. Since we know relatively little about the effects of mineralizers and extremely high pressures, let us assume that at sufficient depth below Oahu such crystallization is possible.

For example, 10 parts of Honolulu nepheline basalt magma (Table 10, Column B) would be left if 90 parts of Koolau basalt (Column A) should crystallize from a magma (Column C) that is strikingly similar to the primitive olivine basalt (Column D). These calculations are illustrated graphically by Wentworth and Winchell (1946, Fig. 3).

A magma 90 per cent solid probably could not yield up its 10 per cent of residual liquid after attaining such consolidation. But if settling takes place during the earliest stages, 50–60 per cent of the magma might solidify without preventing the partial removal of residual liquid from the crystal mush. Perhaps the conditions for such removal by filter-pressing were attained as a result of the 3000-foot submergence of Oahu, Maui, Lanai, and other islands near by, from the Lualualei (−1800-foot) stand to the Mahana (1200-foot) stand of the sea. Other smaller submergences are listed in Table 2. The pressure so produced may also have started or extended the rifts that gave vent to the Honolulu eruptions. Into these rifts liquid magma was pressed, either to erupt immediately as basanite or to differentiate still further, finally to be erupted as nepheline basalt. Table 10 shows that 30 parts of Honolulu series basanite (Column E) and 70 parts of magma like that of the Koolau series (Column A) might separate from a parent magma with composition (Column F) approximately

the same as that of the primitive Hawaiian basalt (Column D). Basanite may be differentiated to nepheline basalt by removal of either hypersthene basalt or olivine basalt. In this step-by-step manner, then, perhaps some of the 10 per cent of residual liquid postulated above for the source of the Honolulu series lavas might be erupted.

TABLE 10.—*Differentiation of east Oahu lavas*
(Calculated to 100 per cent, excluding H_2O and minor elements.)

	(A)	(B)	(C)	(D)	(E)	(F)
SiO_2	50.98	37.95	49.68	48.98	43.76	47.07
TiO_2	2.36	2.70	2.39	2.30	2.65	2.46
Al_2O_3	15.10	11.69	14.76	14.08	12.13	14.08
Fe_2O_3	3.42	5.87	3.67	5.06	3.62	4.15
FeO	7.63	8.37	7.71	8.06	9.18	7.85
MgO	7.75	12.72	8.25	7.16	12.63	9.24
CaO	9.27	13.80	9.72	9.05	11.10	10.63
Na_2O	2.87	4.62	3.04	3.57	3.46	3.40
K_2O	.35	1.09	.42	1.25	.99	.57
P_2O_5	.27	1.19	.36	.49	.48	.55

(A) Average composition of 10 Koolau basalts (recalculated from Wentworth and Winchell, 1946, Table 4, Column A).
(B) Average composition of 6 nepheline-melilite basalts (recalculated from Table 7, Column B).
(C) 90 parts of (A) plus 10 of (B).
(D) Average composition of 43 Hawaiian lavas (recalculated from Cross, 1915, p. 87).
(E) Average composition of 2 Honolulu basanites (Table 7, Columns 13, 14).
(F) 70 parts of (A) plus 30 of (E).

Such an *ad hoc* mechanism is not very satisfying, but, in view of the general acceptance of crystallization as the principal cause of differentiation, it seems proper to include at least a brief mention of it.

DISCUSSION

Tracing the course of differentiation of the Honolulu series is not simple. Variation diagrams representing the entire list of analyzed rocks from east Oahu clearly indicate a difference between the Koolau and Honolulu series. Figure 6 shows the variations of the several constituents plotted against $\{1/3\ SiO_2 + K_2O - 9/10\ Fe_2O_3 - FeO - MnO - CaO\}$, a quantity proposed by Larsen (1938, p. 506) to be used instead of the silica percentage. Another type suggested by Larsen (1938), based upon six variables calculated from the norm, is presented in Figure 7. Both these diagrams show a break in continuity between the Honolulu series and the Koolau series, which is to be expected unless both are descended by the same route from a common parent. In Figure 7 the normative feldspar, total femic minerals, and quartz or silica deficiency are indicated by a circle for each analysis. The circle is tied by a line segment to a dot which indicates the composition of the normative feldspar in a rock saturated with respect to silica but otherwise equivalent to the analyzed one. Position, orientation, and length of the line segment are characteristics of the analysis. Koolau rocks are numbered 1–11 to correspond to the columns in Wentworth and Winchell (1946, Table 4); Honolulu rocks, 12–20 to correspond to the columns in Table 7.

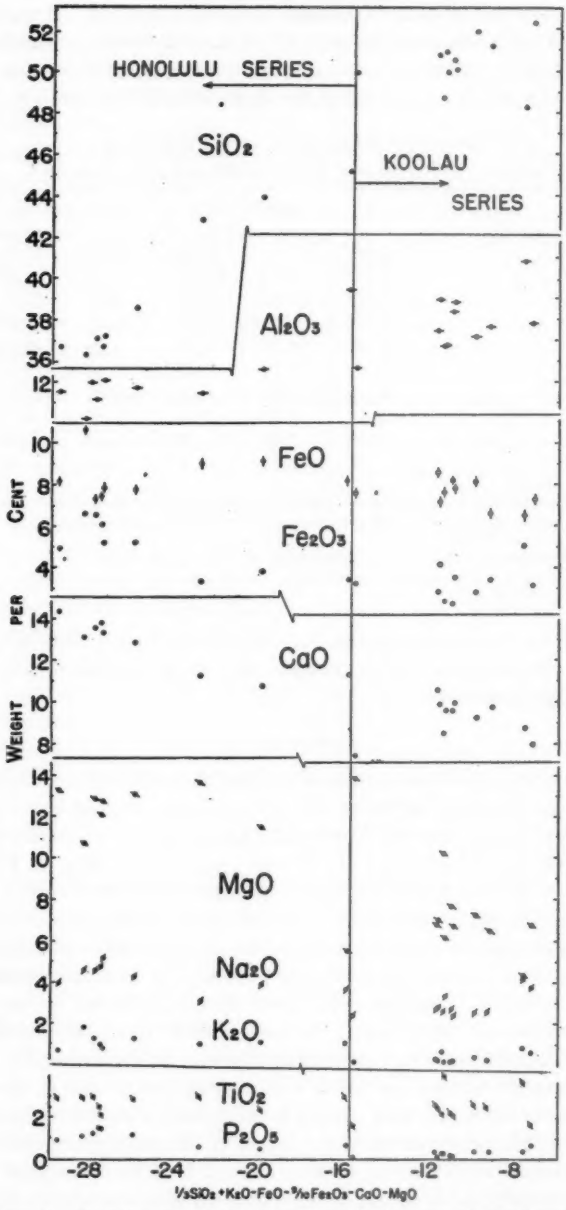

FIGURE 6.—*Variation diagram based upon weighted average of several constituents*
This diagram shows that the Koolau and the Honolulu series are not continuous.

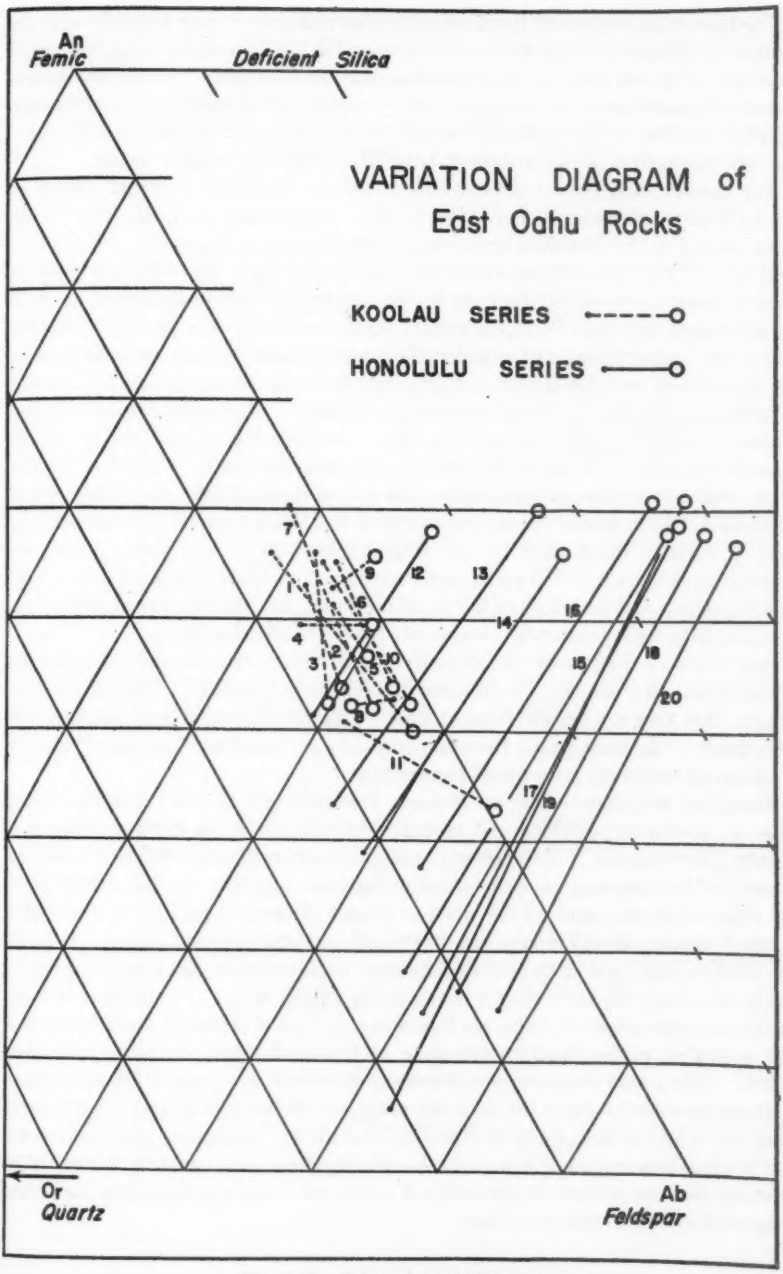

FIGURE 7.—*Triangular variation diagram*
Showing compositions of east Oahu rocks.

The lines which represent the Honolulu series in Figure 7 form a family with the normative feldspar-to-femic ratio nearly constant at 43:57, and the orthoclase nearly constant at 10 per cent of the normative saturated feldspar. Variations toward greater silica deficiency are accompanied by corresponding variations toward greater anorthite content of the normative saturated feldspar, and this trend is followed as the rock varies from linosaite through basanite to nepheline-melilite basalt.

The Koolau rocks show a notable lack of order in variation diagrams, as pointed out by Wentworth and Winchell (1946, p. 75). Silica deficiency in Analysis 9 seems to be related to the Honolulu series rocks when plotted in Figure 7, but there is no field nor microscopic evidence to confirm that possibility. The rock was collected from a massive flow stratigraphically several hundred feet below the top of the Koolau series near Makapuu Point, the eastern tip of the island. The locality is 2000 feet east of the Koko rift line and considerably removed from the nearest rocks showing any evidence of post-Koolau igneous activity. The rock contains more olivine than other Koolau basalts, but some hypersthene is present. The groundmass is too fine-grained to afford reliable micrometric data. Analysis 8 is another variant, partly because it is old. Iron determinations are obviously incorrect. Its line in the diagram probably represents inaccurate data rather than variant rock composition. Analysis 4, like 9, should be representative of the Koolau series. It was collected from a massive ledge close to the stratigraphic top of the series where the dome plunges below sea level on its northwest flank. Analysis 4 appears to be similar to 8 in position and length of its line in this diagram, but the directional sense of the line (*i.e.*, from circle toward dot) is opposite that of the line for No. 8.

Regardless of the process of differentiation involved, the Honolulu magmas are probably not all from one and the same differentiation chamber. The age relations suggest that they are derived from at least 4 different chambers, and possibly from 10 or more. The most recent Honolulu eruptions are Koko and Tantalus (Table 2); yet these represent the extremes of composition.

The oldest eruptions—those on Mokapu Peninsula (Pl. 1) and the islets offshore from it—produced nepheline and nepheline-melilite basalt, as if representative of greater differentiation. If the several magma chambers in which differentiation produced the Honolulu magmas were formed at the same time, then the size of the individual chamber feeding each of the vents or groups of vents should affect the results. A small chamber should require less time to differentiate to a given extent and should therefore be ready sooner to produce nepheline-melilite basalt than a large one, which might still erupt basanite after a considerably longer period. A chamber of intermediate size would produce the late Tantalus eruptions of nepheline-melilite basalt or the somewhat earlier basanite eruptions of Diamond Head, Kaimuki, and Black Point. Only a very large one would produce the late Koko group of basanitic lavas. This agrees with the facts, for the Koko eruptions probably produced more material than any other similar group of Honolulu eruptions. Fortuitous variations in size of the chambers require a less complex and therefore more probable history of intrusions than the alternative postulate of a series of intrusions producing the several magma chambers at different times.

TABLE 11.—*Age and differentiation subdivisions of the Honolulu series*

Age		Subgroup and rift	Vents
Name	Stand (Feet)		
Kahipa	−300	Mokapu Peninsula	Hawaiiloa Pali Kilo Moku Manu Ulupau Mokolea
Kaena	95	Kalihi (Haiku rift)	Kalihi Haiku
		Nuuanu (Tantalus rift)	Kaneohe Luakaha Makuku (Rocky Hill group—independent?)
		Aliamanu (Salt Lake group)	Aliamanu Other buried vents?
		Pali (independent)	Pali
Kaena Laie	95 70	Kaau (Kaau rift)	Kaau Mauumae
Waipio	−60	Ainoni (Kaau rift)	Ainoni Maunawili Training School
		Salt Lake (Salt Lake group)	Salt Lake Crater Makalapa Unnamed
		Diamond Head (Kaau rift)	Diamond Head Kaimuki Black Point
		Kamanaiki (Haiku rift)	Kamanaiki
		Punchbowl (doubtful rift—possibly Haiku?)	Punchbowl
		Castle (doubtful rift)	Castle

TABLE 11—*Concluded*

Age		Subgroup and rift	Vents
Name	Stand (Feet)		
Kapapa	5	Koko rift	Manana Kaohikaipu Kaupo Kalama Koko Crater Kahauloa Dike Hanauma Bay Koko Head vents
Modern	0	Tantalus	Tantalus vents Sugar Loaf vents Round Top vents

Time relations of final eruptions are listed in Table 2, and petrographic and chemical relations in Tables 3 and 7. Table 11 summarizes the subdivisions of the Honolulu series needed to explain the various compositions and ages of the lavas on the basis of the above discussion. In every case except one the earlier eruptions from a given rift or source produced less differentiated lavas and the later eruptions more highly differentiated products. The Diamond Head subgroup of the Kaau rift is the apparent exception; basanite was erupted after the Kaau Crater and the Ainoni subgroups had ejected nepheline-melilite basalts. It seems necessary, therefore, to postulate at least a semi-independence of a Diamond Head magma subchamber from the chamber that supplied the rest of the vents of the Kaau rift. These two divisions of the Kaau rift (Diamond Head and Kaau-Ainoni subgroups) might reasonably represent separate injections of different size (or age?) into dikelike reservoirs in the south rift of the Koolau volcano, the preëxistent structure of which would account for the linear arrangement of the Kaau and Diamond Head groups, whether related or not.

The Haiku rift emitted the Kalihi-Haliku magmas, and later the Kamanaiki; the relation of these two subgroups in the differentiation series is not determined chemically because only the Kalihi flow was analyzed. Microscopically, the Kalihi and the Kamanaiki flows are similar, but the latter contains slightly more melilite, suggesting that the predicted chemical relationship may hold good in this case also.

SUMMARY

Overwhelming evidence from the field effectively rules out the theory of limestone syntexis in explaining the differentiation of the Honolulu series of southeastern Oahu. Some of the most extremely alkalic members of the series are so situated that their dike feeders could not reasonably have encountered sediments of any kind; and some of the least alkalic have actual fragments of calcareous reef rock in their tuffs, having come to the surface through more than 100 feet of sediment.

The high content of mineralizers in the Honolulu series lavas suggests that mineralizers may have affected the process of differentiation. Perhaps they were the principal active agent; however, their most certain function in the process was to lower the temperature of final consolidation of the residual magmatic solution, allowing greatly increased time for extreme differentiation to take place from a primitive olivine basalt magma. Crystallization of hypersthene rather than olivine from a magma already slightly deficient in silica would be sufficient to accomplish the initial desilication of the primitive basalt; possibly the high pressure of very deep crystallization or the abundance of mineralizers might produce this unexpected reaction. Further differentiation by more conventional processes might then account for the extreme differentiates of the Honolulu series. Certainly special conditions seem necessary if crystal fractionation is the principal agent of differentiation. Further study of the whole Hawaiian petrographic province, both in the field and in the laboratory, will probably be required before a thoroughly satisfactory theory can be offered to explain the origin of the Honolulu series.

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KOOLAU BASALT SERIES, OAHU, HAWAII

BY CHESTER K. WENTWORTH AND HORACE WINCHELL

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ABSTRACT

The Koolau volcanic dome forms the eastern and larger part of the island of Oahu. It rises to somewhat over 3000 feet above present sea level and is composed almost entirely of thin basaltic lava flows. The visible flows were erupted from vents along a fissure system more than 30 miles in length and trending parallel to the main axis of the Hawaiian archipelago. The fissure system is marked by swarms of subparallel dikes in a band 2 to 5 miles wide. The rock formation marked by the dikes has been called a dike complex. In the southern half of the dome the crest and fissure portion

has been cut away by erosion from the east, but the forms and structures which remain indicate that the dome at present sea level was never more than about 20 miles wide and that its form was greatly elongate, consistent with its growth about a linear vent system. Indications that faulting took a significant part in the reduction of the southern part of the windward slope are suggestive, but no direct proof has yet been found.

The remainder of the dome has been profoundly dissected to the stage of mid-maturity though enough remains to everywhere indicate its general original form. Following the period of most pronounced erosion there was a series of late eruptions both around the margins and in the interior of the southeastern part of the dome, giving rise to lava flows and pyroclastic cones of ultrabasic composition named the Honolulu series as described by Winchell (1946). Presence of these late rocks in various forms, distributed about Honolulu has attracted petrographic attention to the neglect of the main Koolau series. Following extensive field study and cutting of many hundreds of thin sections in connnection with water-supply studies, nine specimens have been analyzed with particular reference to the problem of variation. No indication of significant or systematic variation in chemical composition has been found, despite the collection of samples from widely separated points and from various depths in the dome. The Koolau basalts are slightly more silicic than most of the "normal Hawaiian basalt" averages heretofore known. Attempts have been made to derive the Koolau composition on various hypotheses, but none having independent basis of plausibility has been developed.

INTRODUCTION

PURPOSE AND SCOPE OF STUDY

The Koolau[1] Range forms the eastern and larger part of the island of Oahu, with its lavas surrounding and overlapping the somewhat eroded older Waianae Range to the west (Fig. 1). Honolulu stands on the coastal plain and lower leeward slopes of the southeastern third of the Koolau Range. Because of its proximity to Honolulu, the Koolau landscape has been familiar to more people than any other part of the Territory, but active volcanism attracted the attention of most visiting geologists to the larger island of Hawaii. Only a few of the more striking or unusual features of Oahu were described in detail by early students.

Particularly notable is a series of secondary craters and lava flows formed from vents mostly near the shore of the southeastern end of the Koolau Range and separated from the Koolau lava series by a great erosional unconformity. The name Honolulu series has been applied to these late volcanic rocks (Stearns and Vaksvik, 1935, p. 98–165). These rocks contain less silica than those of the Koolau series, a condition which finds expression in the presence of nepheline and melilite. The petrography of the Honolulu series is dealt with by Winchell (1946).

In this paper we summarize the known petrography and volcanic features of the Koolau mass. This volcanic dome, like some others in Hawaii, appears remarkably uniform throughout, and we particularly examine this general impression more critically. Great variations necessarily exist in the detail and accuracy of information. For much of the northern part of the range we have only scattered observations, adding very little to the studies made by Stearns (1935; 1940). The section

[1] Pronounced *Koh-oh-lau*, to rhyme with now. The word in Hawaiian means the windward or weather side.

of the leeward slope extending from Wailupe Valley to Ewa, however, has been surveyed in considerable detail with large parts mapped at the scale of 1:6000 (Wentworth, 1938–1945). The remainder of the leeward slope of the range to the Schofield saddle has been examined less critically. In the entire area, about 14,000

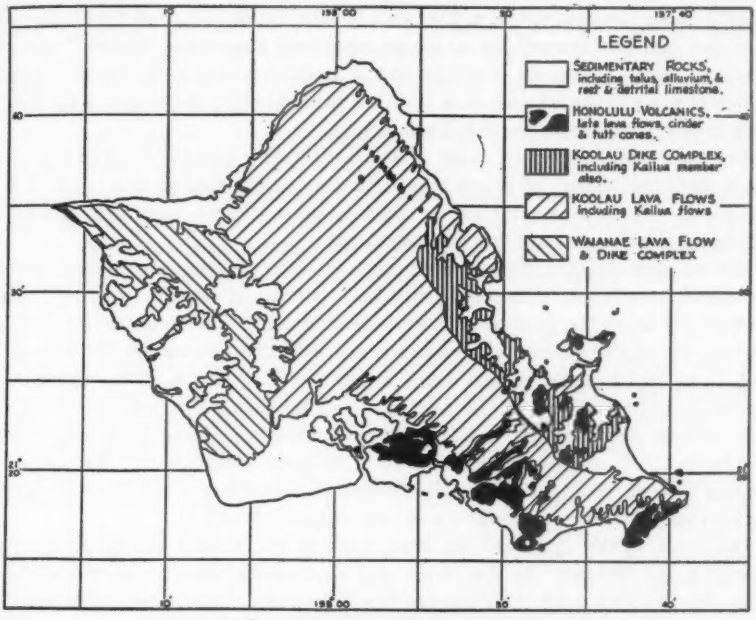
LEGEND
SEDIMENTARY ROCKS, including talus, alluvium, & reef & detrital limestone.
HONOLULU VOLCANICS, late lava flows, cinder & tuff cones.
KOOLAU DIKE COMPLEX, including Kailua member also.
KOOLAU LAVA FLOWS including Kailua flows
WAIANAE LAVA FLOW & DIKE COMPLEX

FIGURE 1.—*Generalized geologic map of Oahu*

Data from Geologic map of Oahu (Stearns, 1939).

field locations have been recorded and structures and contacts mapped. Over 500 thin sections of Koolau lavas and about 300 sections of Koolau intrusives and tuffs have been cut and studied, as well as several hundred sections of the ultrabasic rocks of the Honolulu series. The observations cover a total stratigraphic range of about 2000 feet of lava flows, with a local vertical exposure of 500 to 1000 feet over much of the area.

With this background of prolonged field study of a small area, a few stratigraphic sections have been measured and sampled in other parts of the Koolau range to reconnoiter the entire range as far as possible in time available. Much remains to be done; some further data will come through additional detailed water-supply studies, but complete petrographic studies will require specialized field and laboratory work.

HISTORY OF EARLIER WORK

The earliest travelers noted that the Koolau Range is composed of lava flows. J. D. Dana (1889, p. 91) called attention to many of its features, including the fact that the

"slopes of its southern, western, and northwestern sides remain; but the northeastern are cut off by a great precipice, 20 miles long, which is made for the most part of the edges of the lava streams that slope southward and westward."

From this he deduced that the location of the central vent may have been windward of the present crest. However, Dana apparently did not stress the central crater, since he said elsewhere (1849, p. 258) that "owing to peculiarity of the closing eruption they (distinct craters) are no longer considered a necessary feature." Neither Dana nor those who came after him was in position to recognize the linear distribution of dikes in the dike complex and thus to realize that the source of the Koolau lava flows is a rift zone over 30 miles in length.

Brigham (1868) described many of the outstanding topographic features of the range and implied that, although in most of the existing high portion the lava flows dip southwest, there is evidence in the Koolauloa district (northern half of the windward slope) that some flows dip northeast.

Dutton dismissed the often-favored idea that the curvature of the crest, concave toward the northeast, indicates it may be a portion of the rim of a huge ruined crater. He noted the quaquaversal dips of the lava flows in the northwest (Koolauloa) section of the range, and considered this evidence as favoring his idea of "an axis along which many ancient vents are situated" (1884, p. 212). Dutton discussed the contrast between the windward and the leeward slopes, concluding that more intense erosion on the rainier, windward slopes is sufficient to explain the great destruction on that side and the formation of the great windward cliff, the pali.[2] The present view of the origin of the pali is essentially a merging of this idea with that of Dana, that subsidence on a grand scale was responsible (Pl. 1).

Hitchcock (1900) described the topography of the Koolau Range in detail and discriminated between the Koolauloa and Koolaupoko sections on the windward side—the former is much less dissected than the latter. He described the dipping of the lava flows outward from the crest line of the range but did not identify the dike complex as such. Hitchcock also gave a list of the secondary craters belonging to what is now called the Honolulu series.

E. S. Dana (1889) presented observations on the petrography of the Hawaiian Islands but included very little relating to the Koolau volcanic series. Cross (1915) prepared a much more complete statement on the petrography of Hawaii including analyses of several ultrabasic rocks from southeastern Oahu but only one analysis of Koolau basalt. Thus the Koolau Range remains little known petrographically.

Palmer (1921) prepared a manuscript on high-level ground water in the Honolulu region, dealing with the general characteristics of the valleys from Halawa to Kuliouou. He noted the greater concentration of dikes and sills in the zone near the crest of the Koolau Range but did not describe these as a dike complex.

Stearns and Vaksvik (1935) made the first systematic areal and structural survey of Oahu and of the Koolau Range. As a result of detailed field observations various topographic, structural, and petrographic features were described for the first time. Stearns was first to describe the major rift zone of the dome, giving it the name dike complex. This was mapped as a belt 3 or 4 miles wide and nearly 30 miles long,

[2] Hawaiian word meaning cliff or precipice, pronounced *pah-lee*.

in which the deeper lava flows are intruded by a great many dikes, mostly vertical and parallel with the trend of the present crest and with the axis of the dike complex. The southeastern part of the dike complex lies almost wholly northeast of the present eroded crest of the range. Its southwest margin is commonly a little less than a mile northeast from the crenulate crest, and its axis lies about 2 miles from that crest (Stearns and Vaksvik, 1935, p. 95–97). The exposed part of the dike complex is narrower and less continuous in the northwest part of the range. Toward the end it appears only as a row of inliers exposed where certain deep stream channels cut through the overlying flows.

Stearns gave five reasons for assuming that the volcanic center of the Koolau dome was a little north of the peak Konahuanui (Stearns and Vaksvik, 1935, p. 23). He also pointed out that the Koolau dome has undergone sufficient erosion so that it is doubtful if any part of the original surface remains, and he found evidences of truncation of several flows on flow-slope facets east of Manoa. This and other geomorphic and structural features will be discussed at greater length below.

ACKNOWLEDGMENTS

The major part of this study was carried on as a part of the official survey of geology and ground-water resources for the Honolulu Board of Water Supply. We are grateful to Frederick Ohrt, Chief Engineer, for his interest and encouragement throughout the work. At various times, in connection with co-operative water-supply studies and for comparative purposes a considerable amount of field work has been done outside the Honolulu district so that the general conclusions apply to the Koolau Range as a whole. The chemical analyses of Koolau rocks included in this paper were made by F. A. Gonyer, Harvard University, under G. S. A. Project Grant 297-39, which was awarded to the committee on Hawaiian Petrology.[3] Finally, we are indebted to G. A. Macdonald who read the manuscript and made various suggestions for its improvement. Doctor Macdonald assisted in various ways in connection with the project of the committee.

KOOLAU DOME

GEOMORPHOLOGY

The Koolau lava dome[4] was originally built above present sea level on an elliptical plan. The major axis was practically northwest-southeast and 50 miles long. The length of the minor axis was about 20 miles (Fig. 2). The highest part of the dome was probably northeast of the present crest at Konahuanui (3150 feet) near the head of Nuuanu Valley and may have had an elevation from present sea level of 3500 or 4000 feet. Elevations from 2600 to 2800 feet are attained by several peaks in the portion from 4 miles east to about 18 miles northwest of Konahuanui. Those in the northwestern half of the range closely approach the original height of the dome; those in the eastern half are lower and lie somewhat down the leeward slope from the

[3] W. O. Clark, E. S. Larsen, H. S. Palmer, H. A. Powers, H. Winchell, and C. K. Wentworth, Chairman.

[4] Despite the arguments for using the term shield for the Hawaiian lava masses, we prefer the term dome, or volcanic dome, as having long been used in this region and most likely to be understood by the general reader.

original height and position of the axis of the dome because of the encroachment of erosion from the windward side. The approximate original form of this volcanic dome is shown in Figure 2. This map was constructed from the contour map of Oahu, using field data relating to accordant summit levels, forest and soil con-

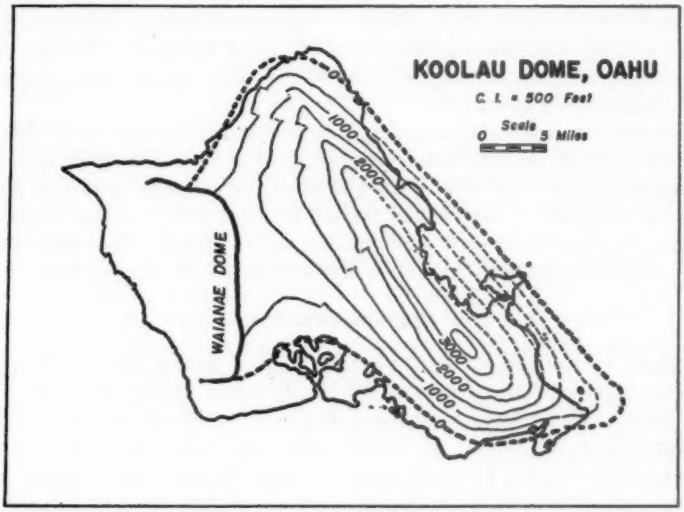

FIGURE 2.—*Contour map showing probable original form of Koolau dome above present sea level*

Data from topographic map, U. S. G. S., and Coast Survey charts.

ditions, weathering, and rock structure. Data from coast charts were used in drawing the contours so as to be consistent with submarine slopes.[5]

The configuration of the western slope as built adjacent to the existing Waianae lava dome was modified by the presence of that lava dome so as to form the present Schofield saddle at about 900 feet elevation. The form of the Koolau dome is well indicated by accordant existing topography along the entire southwest or leeward slope, and along the northern, or Koolauloa portion of the northeast, windward slope. Only in the remaining southern, Koolaupoko, portion of the windward slope can there be any considerable uncertainty as to its original form. From a study of all the facts it seems unlikely that the windward slopes ever extended more than 8 miles northeast of the present summit of the range in the Koolaupoko district. Thus the Koolau dome was always elongate, built over a rift line of source vents at least 30 miles long. The southern branch rift (Kaau Crater to Diamond Head) evidently figured very little in the building of the dome.

The Koolau dome shows two types of erosional modification in two different areas (Pl. 2). The larger area is that mentioned above, the entire leeward slope and the Koolauloa district of the windward slope; the smaller is the Koolaupoko district of

[5] U. S. Geol. Survey, Topographic Map of Oahu, 1/62500, 1938. U. S. Coast and Geodetic Survey, Chart 4110, 1937.

FIGURE 1. VIEW LOOKING WESTWARD FROM THE KING'S HIGHWAY SADDLE NEAR MAKAPUU HEAD
Lava flows of the Koolau series in the windward cliff of the Koolau Range. (Negative W-259)

FIGURE 2. VIEW LOOKING EASTWARD FROM KONAHUANUI
Molokai, east and west, and Lanai are seen on horizon. Rift zone or dike complex lies chiefly along foot of cliff under upper ends of alluvial fans, and lava flows exposed in cliff dip toward the right and toward the leeward margin of the range. (Negative 13802)

WINDWARD SLOPE OF SOUTHEASTERN KOOLAU RANGE

FIGURE 1. PANORAMA OF LEEWARD SLOPE OF KOOLAU RANGE
From ridge between Halawa and Kalauao valleys. Latter valley shows in center of panorama, and range crest shown extends from Honolulu district to middle of range inland from Schofield Barracks. (Negatives 21351-2-3)

FIGURE 2. PANORAMA OF WINDWARD SLOPE OF KOOLAU RANGE
In Koolaupoko section opposite Honolulu. Peak at left is Olomana, isolated by erosion from main crest. Peak to right is Konahuanui, not so much higher than the rest of the crest as appears by foreshortening. Corrugated cliff or pali characteristic of the Koolaupoko slope. (Negatives 13501-2-3)

the windward slope. The larger area is maturely dissected, with many valleys of consequent streams, mostly lacking important tributaries. There are about 45 on the leeward slope and about 15 on the windward Koolauloa slope. Between the streams are very narrow ridges with steep lateral slopes. Many of these ridges at the seaward end broaden to sloping, triangular, little-dissected facets which have been called flow-slope facets (Wentworth, 1926, p. 8–9). These facets commonly terminate inland in an apex which stands at an elevation ranging from 1000 to 1600 feet and which usually is 50 or 100 feet higher than the dissected, narrow ridge extending inland from it (Pl. 2, fig. 1). The form and accordance of these facets indicate clearly enough that in a geomorphic sense they represent the original surface of the dome, an interpretation which is in no sense weakened by Stearns' insistence that parts of the facets in the Honolulu area show the stripping off of one or even several lava flows by erosion (Stearns and Vaksvik, 1935, p. 23). Neither the loss by weathering and erosion of 25 to 50 feet from the original surface, nor the fact that the original surface displayed the flow edges and other irregularities of a lava terrane militates against the designation of these facets as remnants of the dome surface. The view that these facets are destructional surfaces, rather than constructional, seems entirely untenable.

The relatively complete preservation of these facets is evidently due to the reduced rainfall of the lower leeward slopes, to the permeable terrane, and to their position near the margin of the range. The higher, inland parts of the interstream divides are steep-sided and extremely sharp-crested ridges. These ridge crests are mostly cut 100 to 500 feet below the original dome surface but are sufficiently accordant to indicate the form of the dome as a whole. Excepting a few lower valley bottoms which have been filled by an accumulation of terrigenous waste, there are no exposed valley flats developed by erosion at base level. The area is maturely dissected and has very rugged relief.

The Koolaupoko district shows a much more complete erosional destruction than the larger area just described and shows no discernible remnant of the original dome surface. This southeastern portion of the windward Koolau slope is marked by the steep fluted cliff known as the pali. Although this cliff is everywhere steep, the nearly vertical and most conspicuously fluted portion generally stands between the elevations of 600 and 1500 or 2000 feet. It has a declivity of 75°–85° (Pl. 1). From the top of the cliff to the crest of the range is a zone having a general slope of 45°–70° which is commonly dissected to numerous small valley heads and perched alcoves from which drainage converges to fall over the brink of the cliff (Pl. 2, fig. 2).

The base of the pali is flanked by fans of debris, but in many places these apparent fans are only a veneer over buttresses of bedrock which have been left after retreat of the cliff. Although the pali is nearly continuous for about 20 miles, slight interruptions exist at various points where spur ridges branch off at right angles toward the windward coast. Some of these ridges rise like buttresses nearly to the full height of the Koolau crest; they become increasingly numerous toward the northwest, and from Waikane northward for about 5 miles there is a transition from the topographic features of Koolaupoko to those of Koolauloa, previously described.

Between the several spur ridges the pali has been cut back leeward to form a series

of arcs, concave northeastward, at the heads of great theaterlike valleys. Haiku valley, near Kaneohe village, is the most notable of these; it extends several thousand feet leeward of the normal topographic crest line of the range. It was seen by Brigham (1868, p. 357) who referred to it as "a fair type of many valleys on the islands." Viewed as a whole the Koolaupoko area below the foot of the pali cliff is a hilly country separated roughly into valleys by the projecting ridges and remnants of the Koolau mass.

The higher masses of Koolau rock are so irregular in distribution and so separated from the main range crest that it is not easy to visualize them as having been isolated by the normal action of streams consequent on the windward slope. Possibly the structural diversity provided by dikes of the dike complex or by structures associated with central vent activity may have aided an adjustment of streams deviating from the consequent pattern. Block faulting is suggested by the broken character of the topography, and major, linear faulting by the declivity of the main pali; but no direct evidence of either has been found. Despite the analogy with some steep, linear coasts in Hawaii where faulting seems fully demonstrable, steep cliffs are too common in the walls of canyons and along other coasts to count these alone as evidence. Though some minor normal faulting may have contributed to the lowering of the Koolaupoko mass to aid the work of possible marine erosion at a higher stand of the sea and to distort the pattern of stream erosion, we still lack direct evidence and must give major credit to streams.

There are certain respects in which the southern part of the leward slope, as far as Pearl Harbor (the portion opposite the eroded Koolaupoko section of the windward slope), differs from the rest of the leeward slope of the Range. The slope is shorter, and the valleys are dissected more deeply; several have been cut 300 to 1000 feet below present sea level. In some respects, then, this part of the leeward slope is akin to the Koolaupoko windward section, and the range might be divided into a more dissected southeastern end and a less dissected northwestern end, with the boundary running from Waikane valley to Pearl Harbor.[6]

Two interpretations are possible: Either the northwestern end of the range is substantially younger, or the greater length of the leeward slope of this section of the dome is due chiefly to the interference of the adjacent Waianae dome. Both suggestions have merit, and neither can be dismissed categorically. Undoubtedly the greater length of the stream courses of the northwestern part of the leeward slope would impede deep dissection in the parts now accessible, and the widening of the leeward slope is plausibly explained by the fill of lava flows against the opposing slope of the Waianae Range. Furthermore, the lower elevation of the northern half of the original dome (Fig. 2) would probably produce a lower annual rainfall there than in the southeastern half; any such rainfall difference would contribute to the difference in erosion between the northwestern and the southeastern parts of the range, both windward and leeward. No other evidence, especially stratigraphic or structural, is

[6] Hitchcock (1900, p. 20), in discussing the southeastern and northwestern parts of the range, applied the terms Koolauloa and Koolaupoko to both windward and leeward slopes of the respective portions. This is a mistaken and unjustified extension of meaning. In the Hawaiian language the words *koolau*, *poko*, and *loa* mean *windward*, *short*, and *long*, respectively. It is believed that the *poko* and *loa* refer to the short and long topographic slopes of the Koolaupoko and Koolauloa land districts, which are on the windward side of the range only.

known to show discordance of flows or preponderance of late growth at the northwest end of the range. Proponents of the hypothesis of two stages of growth may urge that the limiting of vents of the Honolulu series to the southeastern end of the range indicates earlier and distinct growth of this section, but there is no definite evidence, and we are left only with suggestive but purely circumstantial lines of reasoning.

GENERAL AREAL AND STRUCTURAL GEOLOGY

Stearns and Vaksvik (1935, p. 88–90, 92–98) recognized two conformable formations in the Koolau dome. These were designated as the older, Kailua volcanic series and the younger, Koolau volcanic series. A later interpretation for the Kailua volcanic series (Stearns, 1939, p. 5) states that it consists of late, caldera-filling lavas in the old Koolau center, instead of being an older volcanic mass as originally conceived. The present writers are not prepared to discuss these interpretations.

The Kailua basalts are exposed in an area about 5 miles in diameter on the windward slope of the Koolau dome between Kaneohe and Waimanalo bays and about in the middle of the Koolaupoko section. They lie approximately in the portion of the Koolau mass which was built to the greatest height and has thus been subsequently eroded most deeply. The dike complex, whether of one or two stages of formation, is here exposed more widely than elsewhere, and its dikes lie chiefly in a linear pattern. The rocks of the Kailua volcanic series are amygdaloidal and contain considerable hydrothermal mineral deposits in the vesicles and joints. In this respect and in lower permeability to ground water, the Kailua volcanic series differs markedly from the Koolau lava series. The exposure of the Kailua rocks to alterations associated with vent activity is evident; whether concentration of vent activity in this area led at any stage to a true topographic or structural caldera has not been demonstrated.

Structurally, the lavas of the Koolau lava dome are accordant with the original dome surface described in the section on geomorphology. The entire leeward portion of the Koolau mass consists of lava flows with a few thin beds of red tuff, all dipping 4°–10° approximately toward the nearest point of the margin of the dome. In the upper part of the windward slope in the Koolaupoko section, the flows dip toward the leeward side, because of the leeward migration of the topographic crest of the range from its original position coinciding with the structural crest. However, in that part of the north end of the range which is exposed on the windward side of the dike complex, the dips are 4°–10° northeast, or toward the nearest shore line.

The Koolau basalts, or their residuum in place, underlie nearly the entire Koolau Range (about 280 square miles) with the following exceptions. In the Koolaupoko and Honolulu areas, four chief units have been mapped, as follows: Kailua series, including both lavas and dike complex; Koolau dike complex; Pleistocene alluvium; and the Honolulu series. The alluvial formations and the Honolulu series cover scattered units of area mostly around the southeast third of the Koolau Range, both windward and leeward. In the Koolauloa section the dike complex occupies a large part of the area for the southeastern 5 or 6 miles, and thence to the northwest it crops out only in a line of small inliers where deep channels from Kaluanui to Malaekahana have cut deeply enough to expose it (Fig. 1).

The southeast third of the Koolau Range is flanked on the leeward side by a nearly continuous coastal plain, 1 to 5 miles wide, composed of terrigenous sediments, calcareous reef and other marine rocks, and tuff cones and flows of the Honolulu series. The tuff cones appear to have constituted offshore salients and were connected with the island by fringing reefs before land-derived sediments filled in the area. The inner margin of the coastal plain laps against the flow-slope facets and spurs of the Koolau Range at elevations of 30 to 200 feet according to the width of the plain, and extends up the floors of a number of deep valleys. In the Honolulu sector these tongues rise to elevations of 500 to 900 feet, forming a valley fill laid down when the base level of stream erosion was higher than at present. Lesser areas of coastal plain, formed of coral reef and land detritus without the volcanic components of the Honolulu series, flank the northern part of the Koolau Range locally as shown on Figure 1.

KOOLAU BASALT SERIES

DIMENSIONS OF FLOWS

The bedded character of the Koolau volcanic series is conspicuous in all cliff exposures. There is usually a marked alternation of clinkery or scoriaceous and dense members; the proportions of the two are variable (Pl. 1 fig. 1). Macdonald (1945) estimated the proportion of clinker to total aa in certain sections of the Koolau Range as 15–45 per cent. In unweathered cliffs, the clinkery layers tend to fray out and cave; in weathered exposures the clinkery layers are more consistently oxidized red than the dense ones. In regions of moderate rainfall vegetation generally covers the scoriaceous layers thoroughly, whereas the dense ones support relatively little plant life and usually stand up as low cliffs. Even in nearly vertical cliffs in wet areas the clinkery layers furnish rooting for bands of grass, shrubs, and small trees. Extensive exposures of bare rock are confined to the dry, lower, leeward slopes of the range, but small parts of the windward pali, and many waterfalls and steep canyon walls are bare enough for study by a near-by observer. Only a few, weathered exposures are found in the high, wet, interior parts of the range.

Nearly all collecting of hand specimens is selective, inasmuch as the thick and massive flow ledges are likely to be the freshest and to make the best hand specimens. Collection of hand specimens from the more scoriaceous or vesicular layers is very difficult because of the friability and relatively greater weathering. The advanced weathering and vegetal cover prevent extensive tracing of individual flows in the field. Megascopic features such as thickness, vesicularity, and cliff-forming tendencies can sometimes be used, but these are unreliable criteria for correlations over distances greater than a few hundred feet. Hence, indirect evidence of the horizontal dimensions of flows must be used.

Of 11 historic Mauna Loa flows to 1907, shown on the U. S. Geological Survey's topographic maps of Hawaii, the length of one is 2 miles, five are between 10 and 19 miles long, three are 20 to 29 miles long, and the others are 31 and 32 miles long, respectively. The average length is about 19 miles. The widths of these flows, excluding the common broadening at the lower end and the narrow portion at the

source, are less than 2 miles for nine of the flows, and less than 1.5 miles for six of these. Two flows developed widths up to 5 miles in their middle parts. The minimum width of these 11 flows is between a quarter and half a mile. The mean is probably a little over 1 mile. From these data, which are admittedly very limited, it may be concluded that the mean Mauna Loa flow is 20 miles long and 1 mile wide. There is no reason to suppose that the Koolau flows would differ materially from the Mauna Loa flows, though most radii of the Koolau dome above sea level are not over 5 or 6 miles long, and we cannot be sure what happens to flows when their advancing front becomes submarine.

The thickness of many hundreds of flow units has been observed. The average distance between successive bases of dense members, or between recognizable contacts, is less than 10 feet. Rarely, dense members are 50 feet thick; the thinnest flows are measured in inches. The apparent thickness of flow units in any section is influenced by the nature of the exposure and by the distance from which it is viewed. In stream channels, the more conspicuous flow units are the thicker ones which control the locations of waterfalls. From exposures of this type the impression may be gained that flow units are usually 10–20 feet thick. Estimates of flow-unit thicknesses were made by the writers at several points in exposed cliffs north of Kualoa. Closer to the exposures, more and more junctions were visible, and more flow units were counted in a given interval. The average thickness recognized was less than 10 feet for close examination.

ATTITUDES OF FLOWS

Measurements of the dips of lava flows in the immediate outcrop are difficult because of the irregular, wavy bedding. Measurements based on exposures 20 or 30 feet long may be 5° in error, due to local variations in the surface of the flow. Only in valley walls or other steep cliffs viewed from a distance are measurements accurate. Such measurements show that the flows of the upper 1000 feet of the Koolau dome commonly dip 4°–7° toward the nearest margin of the dome. Table 1 is a summary of groups of dip and slope measurements.

It is not apparent why structural dips recorded on Stearns' geologic map of Oahu should be higher than surface dips at the corresponding points of the dome surface, since on theoretical grounds the reverse might be expected. Considering the mode of growth of a lava dome, it also would be expected that the dips of flows near the margin of the dome would be greater than those near the center; Stearns (1935, p. 93) states that "in general the flows have dips of 3° near the crest and 5° to 10° near the margin of the range." The geologic map (Stearns, 1939) shows 6 observations of dip, averaging 7.5° near the crest of the range and over 1500 feet elevation, and 24 observations below that level and farther from the crest, with an average of 7.2°. Measurements of dip made in the present survey do not show a systematic increase from crest to margin, despite the reasonableness of the assumption.

From variations in the attitude of Koolau lavas it is evident that they flowed over a surface on which abrupt irregularities of 5–10 feet were common. Such a surface would be produced by lava flow units averaging about 10 feet thick. Locally, excesses of slope may be found which show dips of 15° or 20° for distances up to 100

feet. Structures indicating the cascading of a lava flow over a cliff 10 or 20 feet high are occasionally found. All these irregularities are subordinate to the wavy configuration due to slight variations in thickness of the flow units.

TABLE 1.—*Lava flow dips and surface slopes on Koolau Dome*

Portion of dome	Lava flow dips (degrees)	Surface slopes (degrees)
Northwest, windward quarter (Koolauloa)	7.6 (Mean of 8)*	6.0 (Mean of 3)†
Northwest, leeward quarter (Waialua)	4.0 (Mean of 4)*	3.5 (Mean of 4)†
Southwest, leeward (Ewa, Honolulu)	7.5 (Mean of 19)*	6.0 (Mean of 7)†
	5.6 (Mean of 50, Palolo and east)**	
	4.7 (Mean of 27, west of Palolo)**	

* Stearns, (1939).
† U. S. G. S., Topographic map of Oahu, 1938.
** Wentworth and assistants, Geologic Notebooks, Board of Water Supply.

MEGASCOPIC STRUCTURES

The structures found in basaltic lava flows are (1) those due to conditions existing prior to expulsion, (2) those produced during extrusion and emplacement, (3) those developed during the process of cooling, and (4) those produced by subsequent weathering and other secondary processes. The following structures can be found in the Koolau lavas, classified as above:

(1) Aside from phenocrysts of feldspar, olivine, magnetite, and pyroxene, and perhaps some vesicles whose forms and arrangements are attributable to conditions of flow, no structures or other features have been found due to conditions prior to extrusion. No inclusions of deep-seated origin have been found in Koolau basalts, although they are not uncommon elsewhere.

(2) The most conspicuous structures due to flow conditions are the contrasted features of aa and of pahoehoe flows. These terms have been in general use among American and European geologists since the publication of Dutton's report on Hawaiian volcanoes (1884, p. 95–96). *Pahoehoe* refers to the smoother, ropy, "elephant hide" type of flow which has been called "dermolith" by Jaggar (1917, p. 277); *aa* refers to the flows whose surface is characterized by jagged, spiny blocks and loose fragments of all sizes (Jaggar's "aphrolith"). Stearns and Clark (1930) describe the two types of lava surface. Originally the terms *aa* and *pahoehoe* refer to the aspect of the terrane; they are essentially geomorphic terms with no direct structural significance.

Dutton recognized many of the differences of flow behavior and observed that

flows from the same source and of the same composition could be pahoehoe at one place and aa at another, but he reached no conclusion as to the causes. Stearns and Clark (1930, p. 109–110) refer to various investigators who have studied the problem of the origin of aa and pahoehoe. The following are generally granted as facts: (a) Chemical composition does not determine the formation of aa or pahoehoe; (b) Pahoehoe is an earlier and aa is a later stage, and a flow which is pahoehoe near the vent may become aa below, but the reverse is not true; (c) The controlling causes lie in the physical-chemical condition, the state of crystallization, and the gas content (Emerson, 1926). Jaggar (1920, p. 168–169) has shown the importance of the gas content of the "live lava" with its gases trapped in solution, as opposed to the "dead lava" without its gases. The "live" lava produces pahoehoe; the "dead" lava, aa.

Although there may be some doubt as to the suitability of the terms *aa* and *pahoehoe* for petrographic structures as opposed to geomorphic features, it is important to distinguish between the two types since there are differences in their response to weathering and in their hydrologic characteristics at various stages of weathering. Spatial distribution of pahoehoe and aa flows in the Koolau dome may have considerable effect on its hydrology (Pl. 4).

It is also quite important to distinguish between the two types as they are encountered in quarries and excavations. It is not feasible to say categorically whether pahoehoe or aa is the cheaper to excavate, nor whether one or the other is most generally permeable, though real local differences can at times be detected. The clinker of an aa flow may occasion large over-breaks in a tunnel, though even this is not general, and the dense layers of aa flows, despite the large amounts of clinker that must unprofitably be handled, make the only really good concrete aggregate when crushed. Crushed pahoehoe is generally not acceptable for concrete work both for reasons of low strength (rattler resistance) and for the adverse effect of vesicles on the relations of water, cement, and fine aggregate.

On Mauna Loa, flows which start as pahoehoe near their vents may, and often do, become aa lower down. Analogy suggests, therefore, that aa should constitute a larger proportion of the flows near the periphery of a basaltic dome than near the center. Stearns and Vaksvik (1935, p. 93) state that this is the case in the Koolau dome. Obviously, it is necessary to distinguish between pahoehoe and aa flow units exposed only in vertical sections, as in cliffs. The form of junction between successive flow units is one of the possible criteria. Visualizing the rugged surface of aa flows on Mauna Loa, one naturally expects an extremely ragged contact line where another flow overlies an aa flow. This usually does not appear as expected.

A thick aa flow can incorporate, or at least move, any loose material up to the thickness of the invading flow. However, as the loose solid material of the flow itself tumbles down the front, this material would naturally fall into the hollows of the invaded terrane, thus reducing the irregularities of the surface on which the liquid mass would come to rest and solidify to form the dense member of the flow unit. Clinker of the invading flow cannot always be distinguished from that below it. Some compaction of the clinker zone may also take place under the load of the invading flow. These factors probably explain the greater regularity of horizon in

series of aa flows seen in section as compared to the characteristic irregularity of aa terranes seen at the surface.

Further criteria for distinguishing pahoehoe and aa flows are crystallinity and vesicularity. Pahoehoe lava is usually more glassy (especially at and near the surface) and is more regularly vesicular than aa, while aa nearly always shows a holocrystalline texture and has larger vesicles with much more irregular shapes and spacings. The chief structures in an unbroken series of aa flow units are therefore the dense interior zones alternating with clinker zones, the divisions between successive flow units presumably coming in the clinker zones. In such a series, alternation of dense and clinkery material produces a strongly marked aspect of stratification. This appears both directly and through the effects of vegetation and weathering. In an unbroken series of pahoehoe flows, the stratification is less distinct; but the billowy, infolded banding of vesicles and zones of vesicles gives a more diversified structure within the flow itself (Pl. 4, fig. 1). Weathering tends to redden such cellular zones rapidly, and on a wall consisting of such an unbroken series of pahoehoe flows vegetation may cover the wall almost uniformly. Large, irregular vesicles occur scattered in dense aa units (Pl. 4, fig. 2). Pahoehoe vesicles, however, are usually almost spherical and arranged in bands following the curves of the characteristic billowy surface of the flow, as suggested above.

Both aa and pahoehoe flows occur in the marginal parts of the dome. The best estimate of proportion is obtained from drill holes. In about 2000 feet of flows penetrated by drill holes in the Red Hill, Kahauiki, Punchbowl, and Kapahulu spurs, practically 75 per cent of the thickness was composed of aa flows. In only one hole, No. 39, of the Punchbowl spur, did pahoehoe flows slightly preponderate. This is as we might expect. No equally valid data are available for sections nearer the crest.

Well-characterized lava tubes occur chiefly in pahoehoe flows. Some are formed by roofing over the ground in shallow vaults; others are better developed to a tubular section and may be 10 feet or more in diameter. Lava tubes may be filled either during or after the eruption in which they were produced, or if of small diameter they may stand unfilled, or they may be crushed by the superincumbent lavas. Filled lava tubes commonly show concentric banding of vesicles, and joints are concentric or radial or both (Pl. 3, fig. 1). Akin to lava tubes are tumuli or schollendomes, formed by the solidification of a crust of lava over a large "drop" which may afterwards drain out, leaving the crust intact; the lava pressure may, however, break up the crust into blocks which are frequently dislocated and wedged into skew positions.

Limited exposures of surfaces grooved by movement while plastic are occasionally found. Glassy selvage is characteristic of the margins of dikes and sills of the Koolau mass. Some contact surfaces in pahoehoe flows show such glass, or in weathered rock a thin rusty zone may indicate the original glassy surface.

(3) One obvious effect of cooling is the crystallization of the lava flows, another is the joint system which develops by contraction. In a few places Koolau lava flows have developed a somewhat regular columnar jointing, but this is not common except in dikes and sills (Wentworth and Jones, 1940, p. 993–999). Most Koolau

FIGURE 1. DETAIL OF SECTION OF FILLED LAVA TUBE IN KOOLAU SERIES
Exposed in sea cliff at southeast end of range, near Makapuu Head. Vertical diameter about 14 feet. (Negative 11833)

FIGURE 2. DETAIL OF SECTION OF DEEPLY WEATHERED KOOLAU LAVAS SHOWING SPHEROIDAL WEATHERING
Upper 2 feet at rear consists of eolian grit and soil pellets deposited in recent time after deflation from exposures similar to that shown in foreground. (Negative 13173)

FILLED LAVA TUBE; WEATHERING OF KOOLAU ROCK

FIGURE 1. DETAIL OF A PAHOEHOE LAVA FLOW
Showing characteristic involution and alignment of vesicles. (Negative 21008)

FIGURE 2. DETAIL OF A SINGLE AA LAVA FLOW
Showing dense interior with large, irregular vesicles, and top and bottom clinker layers. (Negative 12117)

STRUCTURES IN AA AND PAHOEHOE

flows are broken by joints into nearly equidimensional blocks. The joint system has a spacing comparable to the thickness of the flows. Such jointing in quarries largely prevents the economic production of blocks weighing more than a ton. Single blocks of 5 or 10 tons may be obtained rarely, but general production of such blocks from any known Koolau quarry is impracticable.

(4) Mechanical disruption and erosion of Koolau lava flows would be very rapid under conditions of physical weathering such as prevail at elevations of 10,000 feet or more on Mauna Kea (Gregory and Wentworth, 1937). However, under the subtropical conditions of lower elevations the predominant weathering is chemical and is discussed in the following section.

EROSION AND WEATHERING

The most systematic consideration of weathering is represented by the U. S. Soil Survey map of Oahu. Table 2 is based on this map and the accompanying text (Foster, 1939).

Weathering depends on temperature, rainfall, soil stability, soil drainage, and other factors; land-slope and soil-water behavior are important. The lower Koolau slopes (where sublateritic soils indicate oxidation and the relative accumulation of iron) contrast with the upper slopes where reducing conditions and loss of iron are prevalent. In the lower zone there is little soil movement, temperatures are high, and rainfall is generally less than 60 inches. In the upper zone soil movement is more marked, temperatures are lower, and rainfall is much higher, favoring a forest cover, humus accumulation, and the loss of iron. A special condition of this higher zone is represented by small residual areas where soil movement is very slight and where exceptionally effective reducing conditions have resulted in the formation of thin layers of ceramic clay (Wentworth, Wells, and Allen, 1940).

In the discussion of weathering of lava flows in Hawaii, emphasis is placed on the deeply invasive character of the process. This deep invasion to tens or hundreds of feet is characteristic of warm climates (Merrill, 1906, p. 271-272; Russell, 1889); it is also particularly favored here by the open structure of the lava mass, with horizontal openings between and in flows, and vertical joints across flows. The soil profile is imperfectly developed in Hawaii in relation to the surface of the ground; however, in relation to avenues of water and air movement through the rock mass, well-marked soil profiles, or what might better be called *weathering radii*, are very well developed. Thus the degree of alteration often is not so closely related to the depth below the surface as to the distance inward, toward the kernel, from major joint boundaries where water circulates and where weathering is most complete. This pattern of invasion complicates development of a simple soil profile (Pl. 3, fig. 2).

In Hawaii the soils tend to develop a pelletlike structure which increases the capacity to absorb rainfall and renders them exceptionally resistant to soil erosion (N. E. Winters, personal communication, 1939). This characteristic and the heavy forest cover help maintain a thick and nearly continuous soil and subsoil mantle even on very steep slopes. Locally the deeper weathered material becomes rammed into a compact mass which can stand in steep slopes.

For elevations above 100 feet, except the Schofield saddle, the rainfall averages over 100 inches annually. High rainfall, steep slopes, and great roughness tend to increase the rate of weathering. Furthermore, chemical weathering at the surface

TABLE 2.—*Soil areas of Koolau Dome*

Soil class	Distribution	Elevations	Temperatures*	Rainfall (inches)	Type of soil and process
I	On coastal plain areas, none on Koolau rock as such.	Low	High	10–40	Coral sands, dunes, shallow loamy soils, etc.
II	Lower areas between coastal plain and upland and on valley bottoms.	Moderate	High	15–80	Derived from alluvial, colluvial, and marine materials. Great diversity of texture.
III	Large areas in Schofield Saddle District, smaller areas on mid-slopes east of Diamond Head and in Kaneohe-Kailua section.	From near sea level to 1200 feet in general.	Medium	About 60	Red-brown loams residual from lava of basaltic and andesitic (?) types. In this area generally rain fall and evaporation are approximately equal.
IV	In a mid-elevation fringe above Type III in the Schofield Saddle area and small areas in the Kaneohe-Kailua area.	Above Type III	Lower than in Type III by 2 degrees and with more annual range.	60–125	Soils residual from lava flows and with surface soil distinct in color and structure from underlying material.
V	Main, continuous upland central area of Koolau dome, approximately two-thirds of area underlain immediately by Koolau lavas.	Higher	Lower	High mostly 100–300	Soil material removed so rapidly that normal soil development is rare, oxidation is retarded, and reduction increased.

* The entire temperature range is slight. Mean annual air temperatures of 73 to 76 degrees are high; those 60 to 65 degrees are low. Soil temperatures differ by little from these means except very near to the surface.

and a more or less impermeable mantle rock cause a high percentage of run-off during storms and a moderate continuity of runoff in some stream channels. The lower courses and parts of the upper courses of streams are clogged with coarse gravel deposits that move only rarely. Lateral slopes adjacent to the stream channels are flanked by thick accumulations of detritus which collect faster than the streams can remove it. Thick deposits of old alluvium, thoroughly weathered and rammed

under 20 to 500 feet of overburden, cover the lower valley bottoms with a mantle that has been a stable, somewhat indurated formation since late Pleistocene time. On high and intermediate mountain slopes the alluvium is less weathered, more permeable, and obviously much younger than that in the valley bottoms. In these upper areas the mantle rock is subject to slow creep and occasional landsliding; but on slopes as steep as 60° it accumulates to a thickness of 10 feet, and on old, residual facets the thickness of transported and residual weathered material may reach 50 to 100 feet. The formation and slow movement of this material is a part of erosion, as likewise the chemical weathering by which its composition is modified; but the lack of physical weathering tends to make the process of land sculpture less spectacular than it is in many other regions.

PETROGRAPHY

GENERAL DESCRIPTION OF THE LAVAS

Texturally the lavas of the Koolau Range vary but little. They may be described as intergranular-porphyritic, with variations in the groundmass toward equigranular or toward felty textures depending upon relative absence or abundance of plagioclase laths. Some lavas contain appreciable amounts of glassy base, making the texture intersertal-porphyritic. Other textural phases are represented by occasional variant specimens but are not common.

Phenocrysts constitute 0 to 50 per cent of the rock; they are usually olivine, orthorhombic pyroxene, or plagioclase, or any combination of these in any proportion. Cross (1915, p. 18–20) describes a number of Koolau basalts, all of which come under the above description. E. S. Dana (1889, p. 466) described one Koolau basalt in which olivine phenocrysts made up two thirds of the bulk of the rock. The writers' experience indicates that this is plausible, as a number of olivine-rich flows occur alternating with plagioclase-rich flows in Wiliwilinui ridge, just east of Diamond Head, and elsewhere. Some of these olivine-rich flows contain at least 50 per cent olivine phenocrysts; the alternating plagioclase flows contain an estimated 30 to 50 per cent of plagioclase phenocrysts. One of the flows exposed in upper Moanalua Valley contains plagioclase tablets ½ to 1½ inches in diameter which constitute about 40 per cent of the volume of the rock.

Augite does not appear as phenocrysts. Magnetite and ilmenite, hereafter referred to as ore minerals, frequently are included in olivine phenocrysts and undoubtedly crystallized in part before extrusion; these ore minerals appear to crystallize almost without break from before extrusion until after all other minerals have finished crystallizing. They are very rarely or never included in feldspar crystals.

Olivine phenocrysts frequently show iddingsite rims, sometimes at and sometimes just inside the boundaries of the olivine. Such iddingsite in olivine phenocrysts has been interpreted as a product formed only during the short time when the lava was near the vent or actually moving; when the iddingsite is not at the actual boundary of the grain, further olivine must have been deposited during the later crystallization of the lava (Möhle, 1902, p. 84; Ross and Shannon, 1925; Edwards, 1935 and 1938). This relationship has recently been discussed by Macdonald (1940, p. 155–156),

with reference to the basaltic flows of Kahoolawe, Hawaii. The olivine rims of olivine phenocrysts generally have the same crystallographic orientation as the centers, even though separated therefrom by the iddingsite. The mean index of refraction of the olivine is 1.680 to 1.690, and the optic axial angle is near 90°, indicating a composition near the middle of the chrysolite range, or close to 15 molecular per cent of fayalite, 85 molecular per cent of forsterite.

Orthorhombic pyroxene with very large optic axial angle and with a mean index of refraction close to 1.680 is found in Koolau lavas more frequently than not. As noted by Cross (1915, p. 19) its textural role is similar to that of olivine. The composition of the hypersthene, determined optically, is about 15 molecular per cent ferrosilite. This mineral is present in seven of the nine specimens of Koolau lavas analyzed for this study.

Plagioclase, usually slightly zoned labradorite, forms phenocrysts in some Koolau lavas. The zoning is normal, from calcic core to sodic periphery, and only very rarely shows any reversal of this relationship. The most calcic cores commonly observed have been determined by extinction angles as calcic laboradorite, near 70 molecular per cent anorthite; 65 per cent anorthite is an average figure. The rims of these phenocrysts usually have anorthite content around 55 per cent, although one or two examples have been found where the composition is close to 50 per cent anorthite.

The groundmass minerals of the Koolau lavas are feldspar, olivine, rhombic pyroxene, augite, ore, sparsely distributed apatite, and, in some specimens, glass. Plagioclase usually occurs as small lath-shaped crystals without any special arrangement. In some specimens they are numerous enough to overlap considerably in thin section, forming a felty texture; but many specimens contain less of this mineral, and the groundmass has intergranular texture consisting of more or less isolated fedspar laths surrounded by granular pyroxene. These laths are usually of the order of 0.1 to .01 mm long and .005 mm in diameter, making accurate determination of their optical properties and composition difficult. They appear to be sodic labradorite, corresponding in composition to the peripheral zones of the phenocrysts. In some specimens there is interstitial feldspar which appears to have been almost the last mineral to have crystallized between the other grains. It generally occurs in small grains and aggregates showing weak birefringence and rather low index of refraction. It never occurs in grains large enough for positive identification. The material appears to be potash-bearing feldspar, judging by its optical properties and by a slight correlation between its presence and the amount of potash shown by chemical analysis of the rocks (Macdonald, 1942).

Small olivine grains, sometimes associated with rhombic pyroxene, may be found in the groundmass of some lavas. They are not abundant. Orthorhombic pyroxene in the groundmass is difficult to distinguish from monoclinic types. It has been reported by E. S. Dana (1889) and by Cross (1915, p. 20) who refers to its occurrence as "microphenocrysts of bronzite in a groundmass of augite." We have not seen any orthorhombic pyroxene that does not belong to the phenocryst phase of the rock; euhedral outlines of these small grains and their relation to the surrounding groundmass invariably point rather to their earlier crystallization.

Monoclinic pyroxene forms 30 to 60 per cent of the groundmass and corresponding proportions of the whole rock. Its composition appears to be that of pigeonite; grain sizes commonly smaller than the thickness of the section prevent accurate determination of optical properties in thin sections. Powdered material, studied by immersion methods, was more satisfactory. These small grains of monoclinic pyroxene surround the feldspars in an intergranular pattern. They are equant, probably anhedral, and have smaller grains of ore minerals both in and between them.

Ore minerals, presumably magnetite and ilmenite in variable proportions, occur in all Koolau lavas as equidimensional granules with dimensions very rarely exceeding 0.5 mm and commonly under 0.05 mm. The smallest grains are probably unresolvable particles in glassy portions of the rock; margarites and feathery skeletal forms are not uncommon in the glass also. Octahedral magnetite grains are common inclusions in olivine phenocrysts; ore minerals are usually associated with the granular groundmasses of the lavas. Finally, they may occur as dustlike particles in the glass. These occurrences demonstrate the formation of ores from very early intratelluric stages to very late in the history of crystallization of the magma.

Apatite is found in small amounts. In no case has a thin section of a Koolau rock been seen to contain more than about 1 per cent, and some sections contain only a few tiny crystals. The mineral is rare but very widely distributed in the Koolau series.

Much glassy interstitial material is present in some of the Koolau specimens. Glassy material is usually very dark, sometimes almost opaque with exceedingly fine grained magnetite. It is most common in the dike rocks and frequently appears in chilled surfaces of flows.

DETAILED DESCRIPTION OF ANALYZED SPECIMENS

For many specimens collected in the past in Hawaii the localities are only very imperfectly known. A special effort was made to record accurately the localities for the following analyzed specimens. Locations by latitude and longitude were determined on maps to the scale of 1:20000 and agree accurately with those determined for comparison on the published topographic map of Oahu (U. S. Geological Survey, 1938, 1:62500). Descriptions in relation to highways are given, and photographs of all but one of the sites were taken and are on file. At the time of collecting, a dozen or more hand specimens were taken, and a reserve stock of crushed and properly sampled material for analysis has been retained. The locations are summarized in Table 3.

SPECIMEN NO. 9948: Melabasalt porphyry; Classification: 3 3 12 (Johannsen, 1931).

Koolau basalt series.

Locality: Long. 157° 39′ 42″ W., Lat. 21° 18′ 46″ N., Elevation 120 feet. Road cut on north side, main highway pass, Makapuu Point, Oahu; at road level 50 feet southeast from lower and northwest end of cut, near manhole cover. (Negative W-363).

Megascopic description: Gray, very fine grained, with large vesicles. Probably aa. Considerable number of phenocrysts visible.

Microscopic description: Olivine and orthorhombic pyroxene phenocrysts, in an intersertal groundmass containing labradorite crystals (An_{50}, Ab_{48}) and pigeonitic pyroxene grains, with ore

minerals, held together by glassy material which varies from one thin section to another, between 5 and 20 per cent. Representative section contains about 15 per cent glass in the groundmass.

Analysis, Norm, and Mode: *See* Table 4, Column 9.

SPECIMEN No. 9980: Hypersthene-bearing melabasalt porphyry; Classification: 3 3 12.

TABLE 3.—*Summary of analysed specimens of the Koolau series, Oahu*

Field Number	Locality	Position	Analyst
	Waimea*	North end of dome.	Lyons (1896)
	Nuuanu Pali	Saddle *ca.* 3000 feet below final range crest, near vent axis.	Washington (1923)
9948	Makapuu highway saddle	Near vent axis at east end and slightly less than 1000 feet below original dome surface.	Gonyer
9980	West of Waimea Bay	Near dome shore, north end, and *ca.* 200 feet below dome surface.	Gonyer
9986	Haiku Valley	Near vent axis, *ca.* 2500 to 3000 feet below dome surface.	Gonyer
9991	Waiakeakua Valley	Leeward valley, *ca.* 1500 feet below dome surface.	Gonyer
10396	Waiahole Valley	Windward valley, near vent axis, *ca.* 3000 feet below dome surface.	Gonyer
10398	Palolo quarry	Thick dike in minor vent axis, probably late volcanic.	Gonyer
10403	Makapuu Point summit	Near vent axis at east end, *ca.* 200–300 feet below dome surface.	Gonyer
11320	Moanalua Valley	Leeward valley, inland, *ca.* 1500 feet below dome surface.	Gonyer
10404	Kailua Road	Kailua volcanic series, relations not known.	Gonyer

* In a more widely used reference (Cross, 1915, p. 48), the locality is given only as "Koolau Mountains, Oahu," which is unnecessarily vague

Koolau volcanic series.

Locality: Long. 156° 4′ 16″ W., Lat. 21° 38′ 26″ N., Ledge of dense, light-gray basalt on shore of Oahu, opposite Wananapaoa islet, south of Waimea Bay.

Megascopic description: Dense, light-gray porphyritic basalt with recognizable phenocrysts of pyroxene, olivine, and feldspar.

Microscopic description: Texture somewhat variable, but definitely porphyritic; intergranular in all but one thin section studied. Phenocrysts consist of labradorite, average about 65 per cent anorthite, often in zoned laths, varying from An_{67}, Ab_{33}, to An_{83}, Ab_{17}. More calcic cores, less calcic rims. Olivine phenocrysts have notable rims of yellow-brown mineral, presumably iddingsite.

Hypersthene phenocrysts play same textural role as olivine. Hypersthene composition appears to be about 20 per cent ferrosilite 80 per cent enstatite (2V = about −85°).

Groundmass is composed of pigeonite or augite; feldspar containing about An_{42}, Ab_{33}. Ore minerals are large, interstitial grains, possibly enlarged older grains. Small amount of apatite included in groundmass feldspar. Less than 1 per cent of glass in one of several sections examined.

Analysis, Norm, and Mode: *See* Table 4, Column 4.

SPECIMEN No. 9986: Melabasalt porphyry; Classification: 3 3 12.

Koolau volcanic series.

Locality: Long. 157° 50′ 17″ W., Lat. 21° 24′ 40″ N., Elevation 730 feet in left wall of gulch carrying main flow of water into the left (north) branch of Haiku Stream, Oahu, above Haiku tunnel.

Megascopic description: Porphyritic basalt with small olivine and probably plagioclase phenocrysts, in a slightly vesicular, light-gray groundmass.

Microscopic description: Intergranular porphyritic texture with olivine, hypersthene, and plagioclase phenocrysts. The plagioclase phenocrysts are zoned from An_{63}, Ab_{37} at the core to An_{33}, Ab_{67} at periphery. Neither olivine nor hypersthene constitutes a phenocryst phase of 5 per cent by volume. Although quartz is indicated (2.10 per cent) in the norm, none could be found in the thin sections examined. The groundmass is composed of hypersthene, augite or pigeonite, plagioclase, and ore minerals, with accessory apatite and glass in small traces. It is presumed that the glass hides any free silica present.

Analysis, Norm, and Mode: *See* Table 4, Column 6.

SPECIMEN No. 9991: Melabasalt; Classification: 3 3 12.

Koolau volcanic series.

Locality: Long. 157° 47′ 40″ W., Lat. 21° 19′ 54″ N., Elevation 580 feet, Waiakeakua branch of Manoa Stream at top of fall below Wright monument and rain gauge, and about 150 feet upstream from Manoa tunnel No. 2.

Megascopic description: Rather light-gray basalt, almost without visible phenocrysts.

Microscopic description: Small phenocrysts of feldspar lie in an intersertal to intergranular groundmass. The latter is composed of plagioclase, monoclinic pyroxene, ore mineral, and a little interstitial glass. The ore mineral is predominantly magnetite, but ilmenite is fairly abundant. A few small phenocrysts of olivine (up to 0.5 mm long) are present and are partly resorbed. In one slide they are fresh but in another they are slightly altered around the edges to iddingsite. The plagioclase phenocrysts consist of a core of sodic bytownite, surrounded by a thin shell of medium labradorite. The groundmass feldspar is medium labradorite (N_Y = 1.562).

Analysis, Norm, and Mode: *See* Table 4, Column 7.

SPECIMEN No. 10396: Basalt porphyry; Classification: 2 3 12.

Koolau volcanic series.

Locality: Long. 157° 58′ 18″ W., Lat. 21° 28′ 29″ N., Waiahole Valley, elevation 890 feet, in channel on north side of portal to the tunnel through the Koolau Range.

Megascopic description: Medium-gray rock of very fine grain, with few phenocrysts and few vesicles.

Microscopic description: Intergranular porphyritic texture, with rather abundant (10 per cent) plagioclase phenocrysts and almost as much hypersthene. Some olivine phenocrysts with brown iddingsite rims. Groundmass contains at least 30 per cent feldspar (labradorite), pigeonite, and fine grains of magnetite and ilmenite. Several per cent of glassy material.

Analysis, Norm, and Mode: *See* Table 4, Column 10.

SPECIMEN No. 10398: Diabase; Classification: 2 3 11 or 2 3 12.

Koolau (intrusive) volcanic series.

Location: Long. 157° 47′ 15″ W., Lat. 21° 18′ 15″ N., Palolo quarry, central zone of the complex dike near the inland end of the upper workings, June 1940. Elevation 600 feet.

Megascopic description: Greenish-gray rock of millimeter or larger grain size, without noticeable phenocrysts. Jointing tends to make this particular phase of the intrusive split into wedge-shaped slabs 1–4 inches thick, and 4–10 inches in length and width, all sides being remarkably flat.

Miscroscopic description: The texture is intergranular and locally diabasic. The rock consists of plagioclase, augite, hypersthene, a little olivine, ore minerals, and interstitial alkalic feldspar which

in part is a microperthitic intergrowth. Small acicular grains of apatite are enclosed in the feldspar. The ore minerals are partly ilmenite and partly magnetite. A few hypersthene grains contain cores of olivine; others are enclosed in a thin jacket of augite. The plagioclase is zoned from intermediate laboradorite ($N_Y = 1.564$) in the center to andesine on the outside. The proportions of minerals given in the mode are the averages of three traverses on two slides.

Analysis, Norm, and Mode: *See* Table 4, Column 1.

SPECIMEN No. 10403: Melabasalt; Classification: 3 3 12.

Koolau volcanic series.

Locality: Long. 157° 39′ 19″ W., Lat. 21° 18′ 38″ N., 100 feet south of Makapuu Head triangulation station. Elevation about 647 feet.

Megascopic description: Nonporphyritic, light-gray basalt from ledge of aa. Irregular vesicles in highly variable proportions in different parts of the same ledge. Specimens collected were mostly from a relatively nonvesicular corner of the ledge.

Microscopic description: A few olivine phenocrysts are present. They are partly resorbed and altered around the edges to iddingsite. The groundmass is intersertal, composed of plagioclase, pyroxene, ore minerals, and interstitial glass. Both magnetite and ilmenite are present. The plagioclase is medium labradorite ($N_Y = 1.564$). The pyroxene is predominantly pigeonite, but a few microphenocrysts of hypersthene are present, enclosed in a thin shell of pigeonite. Minute grains of apatite are enclosed in the feldspar.

Analysis, Norm, and Mode: *See* Table 4, Column 2.

SPECIMEN No. 11320: Plagioclase basalt porphyry; Classification: 2 3 12.

Koolau volcanic series.

Locality: Collected from stream boulder in Monanalua Valley. Similar material occurs well up the main right (north) fork of Monanalua Stream and in Haiku Valley and elsewhere on the windward side of the Koolau Range. Longitude of the outcrop is about 157° 50′ to 157° 51′ W., Lat., 21° 23′ to 21° 24′ N.

Megascopic description: The rock is a very light-gray megaporphyry, with plagioclase phenocrysts up to 25 mm in diameter. The groundmass is moderately light gray and aphanitic. Some olivine phenocrysts can be found. The large feldspar crystals appear to form nearly 40 per cent of the rock volume and are very conspicuous; micrometric methods on thin sections give somewhat unreliable percentages for such large phenocrysts.

Microscopic description: The texture is porphyritic, with an ophitic groundmass. Phenocrysts are strongly zoned plagioclase with cores showing as high as 68 per cent anorthite content; peripheries are sodic labradorite of approximately same composition as the groundmass plagioclase. Rare hypersthene and olivine phenocrysts are present; early olivine is completely altered to iddingsite, but in some an olivine rim remains.

The groundmass contains considerable plagioclase, estimated micrometrically at about 40 per cent by volume. Pyroxene in the groundmass occurs as anhedral grains, some large enough to surround small groundmass plagioclase laths poikilitically. Ore minerals present are magnetite and ilmenite, and a small amount of glass fills some of the finest interstices.

Analysis, Norm, and Mode: *See* Table 4, Column 11.

SPECIMEN No. 10404: Melabasalt (altered); Classification: 3 3 12.

Koolau (Kailua) volcanic series.

Locality: Long. 157° 45′ 04″ W., Lat. 21° 23′ 31″ N., Pipeline cut on east side of roadway, 3800 feet north of Kailua Junction.

Megascopic description: Light-gray amygdaloidal basalt.

Microscopic description: The texture is intersertal. The rock consists of calcic labradorite ($N_Y = 1.566$), pigeonite, ore minerals, interstitial finely fibrous chlorite, and a little interstitial calcite. Vesicles are filled with quartz and chlorite. Some nearly homogeneous patches of chlorite appear to be pseudomorphs after original olivine grains. Some larger feldspar grains are cut by tiny veinlets of calcite. Both magnetite and ilmenite, in indeterminate proportions, are present.

Analysis, Norm, and Mode: *See* Table 4, Column 3.

TABLE 4.—*Analyses of Koolau basalts*
(See text for detailed description of analyzed specimens.)

	1	2	3	4	5	6	7	8	9	10	11	A
Specimen number..	10398	10403	10404	9980	*	9986	9991	†	9948	10396	11320	Mean***
SiO_2	52.30	51.94	51.20	50.97	50.80	50.59	50.08	49.88	49.62	48.74	48.28	50.45
TiO_2	1.68	2.58	2.49	2.14	2.55	2.18	2.08	3.97	1.51	2.42	3.70	2.33
Al_2O_3	14.80	14.18	14.62	13.72	14.42	15.34	15.80	13.79	12.68	15.98	17.86	14.94
Fe_2O_3	3.12	2.81	3.43	2.39	2.83	2.23	3.58	9.65	3.21	4.14	5.07	3.38
FeO	7.30	8.14	6.60	7.61	8.53	8.18	7.81	2.61	7.60	7.16	6.53	7.55
MnO	.05	.08	.10	.11	.09	.09	.11	.67	.09	.06	.06	.08
MgO	6.72	7.21	6.48	10.18	6.88	7.64	6.70	6.12	13.86	6.96	4.11	7.67
CaO	7.98	9.24	9.74	8.51	10.58	9.60	9.92	9.59	7.48	9.90	8.76	9.17
Na_2O	3.78	2.52	2.53	2.56	2.70	2.68	2.36	3.30	2.36	2.77	4.14	2.84
K_2O	.60	.35	.21	.61	.30	.11	.17	.17	.15	.22	.82	.35
H_2O-	.23	.12	.18	.08	.06	.27	.28	**	.34	.70	.06	.23
H_2O+	.64	.59	2.20	.61	.31	.64	.74	**	.67	1.19	.31	.73
CO_2					n.d.			**				
P_2O_5	.66	.35	.35	.28	.32	.15	.12	.26	.04	.08	.36	.27
SO_3			.03	.15	n.d.	.17	.15	n.d.	.05	.09	.02	.07
BaO					n.d.			n.d.				
SrO					n.d.			n.d.				
Cr_2O_3		.04		.07	n.d.	.05	.06	n.d.	.19	.04	.04	.05
SUM	99.86	100.15	100.16	99.99	100.37	99.92	99.96	100.01	99.85	100.45	100.12	100.11

Norms

Q	2.16	6.24	8.22	1.02	2.88	2.10	4.74			1.62		2.40
Or	3.34	2.22	1.11	3.34	1.67	.56	1.11		1.11	1.11	5.00	2.22
ab	31.96	20.96	20.96	21.48	23.06	23.06	19.91		19.91	23.58	35.11	24.10
an	21.68	26.41	28.08	24.19	26.13	29.19	31.97		23.63	30.58	27.52	26.69
di wo	5.57	7.31	7.66	6.73	10.21	7.31	6.84		5.68	7.42	5.45	7.08
di en	3.50	4.60	5.30	4.60	6.30	4.60	4.30		4.10	5.10	4.20	4.70
di fs	1.52	2.24	1.72	1.58	3.30	2.24	2.11		1.06	1.72	.66	1.85
hy en	13.30	13.40	10.90	20.80	10.90	14.50	12.30		22.90	12.30	4.00	14.50
hy fs	6.47	6.34	3.70	6.99	5.81	7.52	5.94	††	5.94	4.22	.66	5.54
ol fo									5.32		1.54	
ol fa									1.43		.20	
mt	4.41	4.18	4.87	3.48	4.18	3.25	5.34		4.64	6.03	7.42	4.87
cm									.22			
hm												
il	3.19	4.86	4.71	4.10	4.86	4.10	3.95		2.89	4.56	6.99	4.41
tn												
ap	1.68	.67	.67	.67	.67	.34	.34			.34	1.01	.67
SUM	98.78	99.43	97.90	98.98	99.97	98.77	98.85		98.83	98.58	99.76	99.03

* "Aphyric basalt," Nuuanu Pali, Oahu (Washington, 1923, p. 487).
† "Koolau lava," Waimea, Oahu (Lyons, 1896, p. 424; also in Cross, 1915, Anal. No. 19).
** Analysis of ignited material.
†† Owing to ignition before analysis, calculation of a norm does not yield useful results.
*** Excluding Column 8.

GENERAL COMPARISON AND DISCUSSION

Search of the literature reveals many analyses of basalts of composition comparable to the Koolau rocks. Table 5 shows a number of averages which may be compared with the analyses of Table 4.

TABLE 5.—*Average analyses of basalts similar to the Koolau rocks*

ANALYSES	A	B	C	D	E	F	G	H
SiO_2	50.45	48.69	50.12	50.18	49.87	49.70	50.29	48.34
TiO_2	2.33	2.29	1.37	1.75	1.38	2.23	3.03	2.80
Al_2O_3	14.94	14.00	14.32	14.12	15.96	14.24	12.92	13.27
Fe_2O_3	3.38	5.03	4.61	3.04	5.47	3.66	1.48	2.32
FeO	7.55	8.01	8.52	10.45	6.47	9.96	9.77	9.09
MnO	.08	.41	.43	.19	.32	.17	.14	0.14
MgO	7.67	7.12	6.23	6.42	6.27	6.82	8.07	9.59
CaO	9.17	9.00	8.82	10.67	9.09	9.55	10.84	10.34
Na_2O	2.84	3.55	3.31	2.69	3.16	2.64	2.26	2.43
K_2O	.35	1.24	1.25	.75	1.55	.70	.46	0.58
P_2O_5	.27	.49	.22	.21	.46	.33	.36	0.33
NORMS								
Q	2.40					.90	1.80	
or	2.22	7.23	7.78	4.45	8.90	3.89	2.78	3.34
ab	24.10	29.87	27.77	22.53	26.72	22.01	18.86	20.44
an	26.69	18.63	20.29	24.19	27.52	24.46	23.63	23.63
di	13.63	18.57	17.89	22.42	12.04	16.35	22.37	20.83
hy	20.04	3.46	11.42	17.02	10.67	20.42	21.32	14.46
ol		9.33	4.18	1.48	3.40			7.17
mt (tn)	4.87	7.19	6.73	4.41	7.89	5.34	2.09	3.25
il	4.41	4.41	2.58	3.34	2.58	4.10	5.78	5.32
ap	.67	1.16	.52	.51	1.01	.67	1.01	0.67
Saturation	+2.4	−3.7	−1.7	−0.6	−1.4	+0.9	+1.8	−2.9

(A) Average of 10 Koolau basalts, Table 4.
(B) Average of 43 Hawaiian lavas (Cross, 1915, p. 87).
(C) Average of 29 analyses of lavas from Island of Hawaii (Cross, 1915, p. 87).
(D) Average of 9 preferred postcaldera Kilauean basalts (Cross, 1915, p. 60; "C.-O.-A. group").
(E) Average of 198 analyses of basaltic rocks (Daly, 1933, p. 17).
(F) Average of 43 analyses of plateau basalts (Daly, 1933, p. 17).
(G) Average of "10 good analyses of the most abundant Hawaiian basalts" (Daly, 1933, p. 397).
(H) Average of 49 analyses of olivine basalt, including one olivine gabbro (Macdonald, Ms.).

Koolau basalts are more silicic than the "normal Hawaiian basalt" averages quoted. The average of the rocks designated by Cross (Column D) as the "Camptonose-ornose-auvergnose" group (C.-O.-A.) has been used in Figure 3 to represent the parent magma which has supplied most of the Hawaiian volcanoes.[7] This figure shows graphically the compositions that must be subtracted (possibly by crystal settling) or added (by melting, solution, or other assimilation process) in varying amounts to produce the average Koolau composition.

[7] Just prior to submitting this paper for publication, our attention was called to the average quoted in Column H of Table 5. There is reason to believe that this average will prove to be a more valid starting point for such calculations.

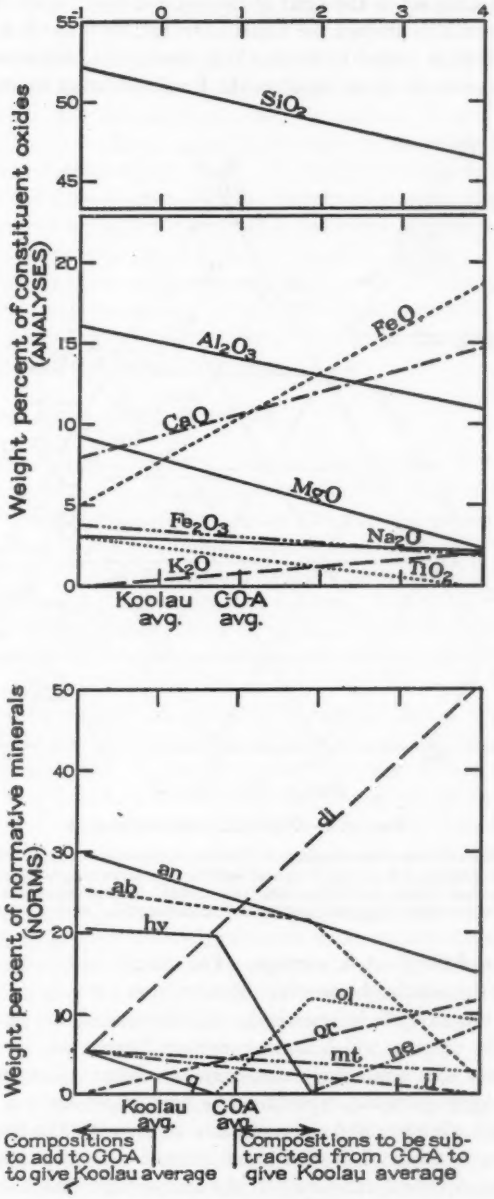

FIGURE 3.—*Difference diagram*

Showing relationship between Koolau average composition and C-O-A average of Cross, and compositions required to transformation from one to the other.

In the figure, analyses to the right of the vertical line, "C.-O.-A. average," may be subtracted from it to produce the Koolau average; those to the left of the vertical "Koolau" line may be added to the C.-O.-A. average to obtain the Koolau; those between the two may be made equal to the Koolau average by subtraction of the

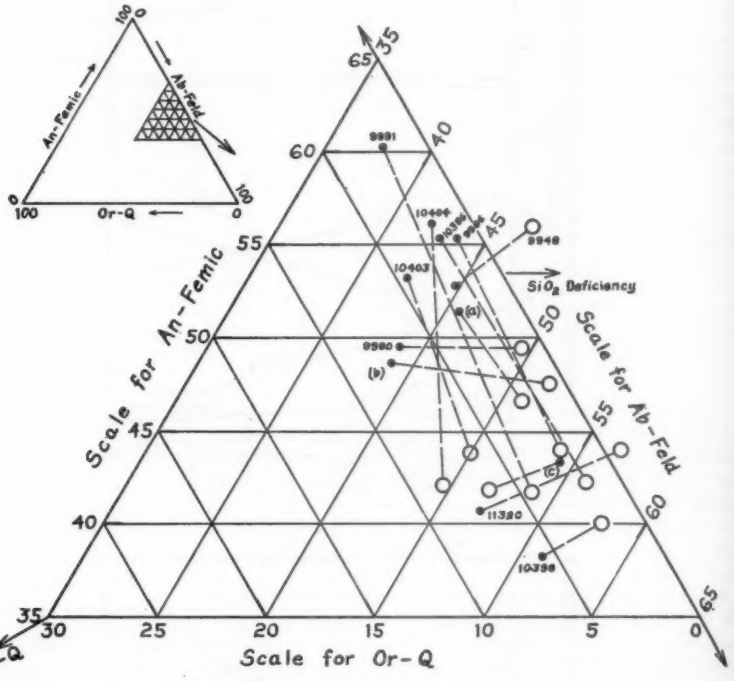

FIGURE 4.—*Triangular variation diagram*

Small key at left shows relation of the enlarged part. The dots represent percentages of orthoclase, albite, and anorthite in the normative feldspar, with its total calculated to 100%. The circles are percentages of quartz (or silica deficiency), feldspar, and femic mineral, total also to 100% (Larsen, 1938). Lettered symbols are: (a) No. 54 (Washington, 1923); (b) Plateau basalt average (Daly, 1933); and (c) No. 19, Koolau (Cross, 1915).

proper amounts of the C.-O.-A. average. The amount to be added or subtracted is determined by the relative horizontal distances between various positions (Koolau, C.-O.-A., and the analysis in question). Similar procedures may be used in the lower part of the diagram which shows corresponding norms.

Figure 3 shows that a relatively small amount of crystallization (25 per cent by weight) of a highly diopsidic nephelinitelike rock might leave a residual liquid so enriched in silica, alumina, and magnesia, and impoverished in ferrous iron and lime as to crystallize to a typical Koolau basalt instead of a primitive Hawaiian basalt. The figure is hypothetical and based on the assumptions that there is such a primitive Hawaiian basaltic composition and that this is reasonably well represented by

the analyses used. Some other average may prove to be more suitable for calculations of this sort.

Variation diagrams of the Koolau basalt analyses are, as a whole, very unsatisfactory. Several types in current use have been tried in an effort to develop significant interpretations. For abscissa scales use was made of (1) the percentage of silica, (2) the weighted average of oxide percentages suggested by Larsen (1938), and (3) the silica-saturation number—*i.e.*, the excess or deficiency of silica for certain minerals in the norm (Larsen, 1938). Variations shown in the Koolau analyses are so small, and the sequences of analyses in the various diagrams are so erratic, that no valid conclusions can be drawn from such diagrams.

The only variation diagram that seems to justify presentation here is shown in Figure 4. This type was proposed by Larsen (1938); for each analysis is shown a dot representing silica saturation and feldspar-femic ratio from the norm, and a circle giving the composition of the normative feldspar.

SUMMARY

The main purpose of the present paper has been, with the aid of the analyses, to offer a unified description of the important features of the Koolau mass, hitherto somewhat neglected in favor of active volcanoes and volcanic masses of specialized interest. The Koolau dome was elongate, built by eruptions from a rift zone at least 30 miles long. We find no evidence of former extension of the dome to windward of the present crest by more than 7 or 8 miles. Loss by combined normal faulting and erosion from the windward side of the dome is considerable but much less than was postulated by early observers who saw in the windward landscape the outlines of a great crater.

The highest part of the dome was probably developed north of the head of Nuuanu Valley. The dikes and mineralization in this area indicate a deep exposure of structures in a vent area, but we find no convincing evidence that a caldera was developed or that it is correct to speak of the central vent of the Koolau volcano. The great length, continuity, and dominance of the main dike complex point to a history of growth in which central vent behavior, if present at all, was subordinate. Moreover, the common development of rift zones and the growth of the Hawaiian volcanoes overrecognized suboceanic cracks suggest that, while central vent dominance may develop in a given volcanic mass, the truly primitive stage is eruption of lava from a rift zone and that this phase may persist throughout the growth of a very large volcanic pile. This is shown by the gross configuration of the Koolau dome and would be by no means nullified even if existence of a Koolau caldera should later be demonstrated by adequate field evidence.

The Koolau Range, as now eroded, consists almost wholly of thin lava flows. Apart from the dikes of the dike complex and dikes of minor rift zones, no intrusive masses have been found. The thick Palolo quarry dike and the buds described earlier by Wentworth and Jones (1940) are but variations of the dikes. The scattered dikes are considerably more abundant in the leeward area from Wailupe to

Kalihi than elsewhere. This distribution suggests formation radial to a central vent, but the evidence is too tenuous to justify postulating such a vent.

Associated with the more abundant dikes in the area mentioned is a greater abundance of palagonite tuff beds, interbedded with the thin lava flows, particularly in a zone from 500 to 1200 feet below the original final surface of the dome. These were at first considered to be due to sporadic hydro-explosions not centered at primary vents (Wentworth, 1941), but accumulation of evidence over a wider area supports the alternative view offered by the junior author that they may represent a temporary phase of repeated explosive eruption from vents in the Nuuanu sector. This evidence would also point to central vent action during a period somewhat earlier than that of final growth of the ultimate dome surface.

No structural evidence has been found to support the postulate of greater age for the southeastern half of the range which might serve as one explanation of the deeper valley cuts and more extensive erosion of that part. No field basis is known for considering the northern part of the dome to be of later completion than the southeastern.

Megascopically, the Koolau lava flows show the same range of variations throughout the whole extent of the exposed dome. In all sections, there are aa flows and pahoehoe flows, and no systematic difference in thickness is known other than possibly the preponderance of somewhat thicker flows in the Schofield saddle area where the structural dips are low.

Petrographically, the Koolau basalts are also remarkably uniform. Some moderate random variations are found between individual lava flows, but the range of variation between flows within a few feet in a local section is as great as that between flows from widely separated points or depths in the dome; we find no evidence of systematic difference either horizontally or vertically. In general the random variations suggest alternation between feldspar porphyries and olivine porphyries due to possible slight differentiation of which the causes are obscure. The differences in chemical composition as shown by the chemical analyses are similar to those suggested by thin section petrography and are even less than might be expected from cursory megascopic examination of the rock.

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FAULT PROBLEMS IN FAULT PLANES

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ABSTRACT

Fault problems are treated by sections in fault planes. Methods are given for deriving from strike and dip of fault and strike and dip of faulted planar elements, such as beds, veins, and dikes, the angles required for drawing in the fault plane. Methods are given for converting field observations on plunge and direction of plunge of linear elements on fault walls, such as grooves and striations, to pitch for drawing in the fault plane. The trigonmetric methods are reduced to substitutions in formulas. The methods using the meridional stereographic net or Postel net are rapid and give results within the limits of accuracy of most field observations. Trigonometric formulas and a net method for converting known thickness to apparent thickness on an inclined fault plane are given.

Examples include translatory and rotatory faults affecting veins, ore shoots, and seams. Among the examples of transverse faults cutting folds is one having the features of some tear faults, in that fault movement was partly contemporaneous with folding of beds.

INTRODUCTION

Fault problems have received extensive treatment. In graphic presentations, vertical cross sections and projections onto a horizontal plane have been the commonly used types of illustration. Drawings of these types are likely to contain so many lines that the reader is confused (Reid, 1909; Billings, 1942, p. 434–453). In addition they give undue emphasis to geometric relations of geologic bodies and components of movement in horizontal and vertical planes. Evidence of movement on a fault plane, such as faulting out, repetition, and offset of tabular bodies, is essentially the result of amount and direction of movement on the fault with respect to the traces on the fault of the tabular bodies, and consequently a drawing to scale in the plane of the fault is, in many cases, the most satisfactory means of illustration. Such drawings have been used in connection with vertical epi-anticlinal faults (Beckwith, 1941, p. 2190).

One hindrance in the use of drawings representing relations in the fault plane has been lack of rapid means of deriving angles on the fault plane from strike and dip

of planes directly observable some distance away from the fault. Graphic and trigonometric methods for deriving these angles are presented, and examples of solutions of problems are given.

This study was begun in March 1942 and during the next 2 months resulted in derivation of the requisite angles and solution of fault problems involving only

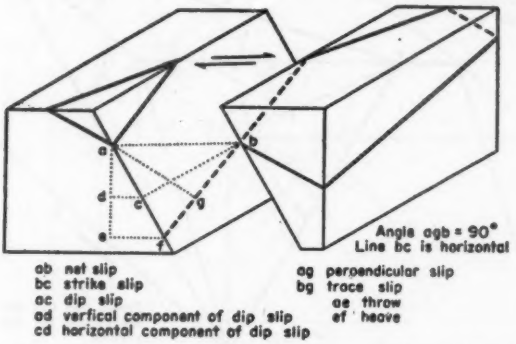


FIGURE 1.—*Oblique-slip oblique fault; movement is translatory*

straight lines on the fault plane. Other duties prevented further progress until late 1945. Bucher (1944) in the meantime published on the net method for deriving some of the angles. He did not, however, apply the net to drawing of curved lines on fault planes and derivation of angles in inclined veins. Inasmuch as net derivation of these angles is conveniently carried out simultaneously with those treated by Bucher, it seems advisable to present the whole sequence.

FAULT TERMINOLOGY

The descriptive terminology here used is that of The Geological Society of America Committee on the Nomenclature of Faults (Reid *et al.*, 1913). The writer has found it satisfactory for use in connection with complex faulting in Rocky Mountain structure, except for the use of "dip of a line", discussed below, and the lack of short terms to designate vertical component of dip slip and horizontal component of dip slip (Fig. 1). These are desirable in order to describe movement in terms of vertical and horizontal rectangular co-ordinates parallel to and normal to fault strike. The terminology of the Committee is now found in many textbooks on structural geology and is correctly used except for the troublesome terms throw and heave. Lahee (1941, p. 209–210) quotes directly from the Committee report (Reid *et al.*, 1913, p. 176) and makes it clear that throw and heave are merely distances appearing in a vertical section normal to fault strike (Fig. 1) and are not necessarily related to the vertical and horizontal components of dip slip. The figures and discussion of Nevin (1936, p. 88–89) are inconclusive and do not make it clear that throw may not be the vertical component of dip slip and heave may not be the horizontal component of dip slip. Billings (1942, p. 136) recognizes that some

geologists use throw and heave in the sense of vertical and horizontal components of dip slip but states that this usage is undesirable.

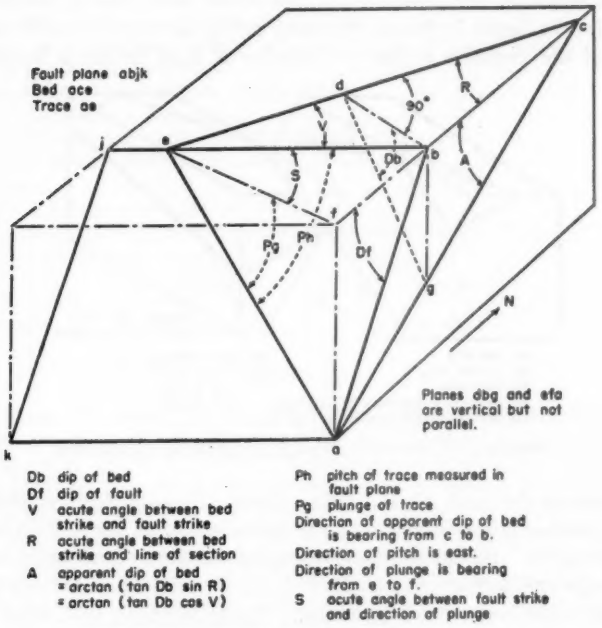

Fault plane abjk
Bed ace
Trace as
Planes dbg and efa are vertical but not parallel.
Db dip of bed
Df dip of fault
V acute angle between bed strike and fault strike
R acute angle between bed strike and line of section
A apparent dip of bed = arctan (tan Db sin R) = arctan (tan Db cos V)
Ph pitch of trace measured in fault plane
Pg plunge of trace
Direction of apparent dip of bed is bearing from c to b.
Direction of pitch is east.
Direction of plunge is bearing from e to f.
S acute angle between fault strike and direction of plunge

FIGURE 2.—*Angles of intersecting bed and fault*

PITCH AND PLUNGE

The pitch of a line in a fault plane (Fig. 2), such as the trace of a dislocated bed or vein, is defined (Reid *et al.*, 1913, p. 181) as the angle between the line and the horizontal measured in the fault plane. This definition now seems to be generally accepted for lines in faults and elongated ore shoots in veins.

The term plunge was proposed by H. L. Smyth (Raymond, 1908, p. 914–915) to designate the vertical angle between a horizontal plane and the axis of an ore shoot; this definition is accepted by Lindgren (1933, p. 155). Billings (1942, p. 135) shows plunge as the vertical angle between a horizontal plane and a line in a fault. For this same vertical angle Reid and associates (1913, p. 181) proposed the term "dip of the line"; the writer believes that this is undesirable, inasmuch as dip should be reserved for use in connection with planes only.

Direction of pitch can be expressed by a generalized statement such as, "Direction of pitch of the trace is east" (Fig. 2), or "The trace pitches east."

Direction of plunge should be expressed as the bearing down the trace. If angle *S* (Fig. 2) is 31°, the direction of plunge is S. 59° E.; this can also be expressed in the form, "The trace plunges S. 59° E."

As applied to folds, the terms pitch and plunge are still loosely used in areal

studies and in some recent textbooks on structural geology, mainly because examples treated are folds with vertical axial planes. The writer believes, in view of possible future use of sections in inclined axial planes of folds, that pitch should be used for the angle measured in the axial plane between a horizontal plane and an axis and plunge for the vertical angle between a horizontal plane and an axis.

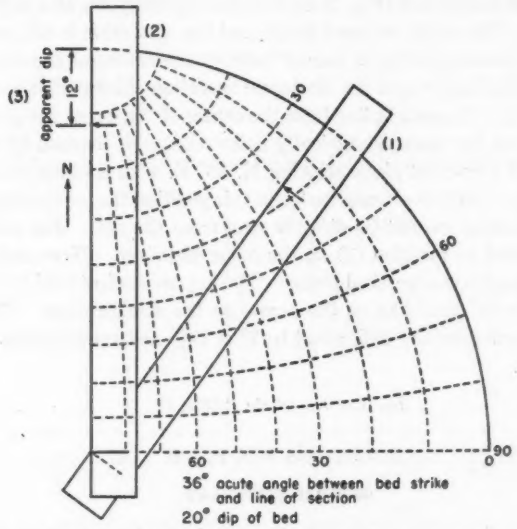


FIGURE 3.—*Apparent dip from dip and angle between strike and line of section*

MERIDIONAL STEREOGRAPHIC NET

The meridional stereographic net came into use in the latter part of the nineteenth century for work in crystallography (Johannsen, 1918, p. 14–19). Fischer (1938; 1941a; 1941b) and Bucher (1944) applied both meridional and polar stereographic nets to solutions of problems in structural geology. The following explanation is given for those who have not worked with the net (Fig. 7). Imagine that the eye is located on the surface of a transparent terrestrial globe at the intersection of the equator and a meridian and that you are looking at the opposite hemisphere. The lines represent meridians and parallels at 10-degree intervals. For use in structural geology it is convenient to consider the plane of the drawing as horizontal with the periphery in this plane and the meridians and parallels beneath it. Numbering the periphery from 0° at the poles to 90° at the equator is convenient for plotting angles in quadrants. Meridians are numbered from 0° at the periphery to 90° beneath the polar diameter. Thus the third meridian in from the periphery on the east side represents the trace on the hemisphere below ground of a plane striking N. and dipping 30° E.

The Postel or angle meridian net is, in certain respects, superior to the meridional stereographic, in that the relative accuracy of different parts of the net is more uniform. Comparison of the meridional stereographic net (Fig. 3) with the Postel

net (Fig. 15) shows that a 10-degree square near the center of the Postel is larger for the same net diameter. This is a distinct advantage in dealing with high dips and plunges. The Postel net used by the writer was 20 centimeters in diameter and marked with lines 2 degrees apart. With reasonable care, angles derived from the net varied 30 minutes or less from trigonometrically computed values.

Use of the net is illustrated (Fig. 3) to find the apparent dip of a bed in a section oblique to strike. The angle between strike and line of section is 36°, and 20° is the dip of the bed. A straightedge is placed through the center of the net and 36° on the periphery. The center and the 20-degree meridian intersection are marked on the straightedge (1). A straight line from the center of the net at the ground surface to the surface of the hemisphere vertically below the point marked by the arrow is the intersection of a vertical plane striking N. 36° E. with a plane striking due N. and dipping 20° E. With the straightedge in this position the vertical angle between this line and horizontal cannot be directly read from the net. The straightedge is consequently rotated to position (2) on the polar diameter. Here angles along the meridian 90° are angles in a vertical plane. The apparent dip (3) of 12° is read from the pole along the 90° meridian to the arrow on the straightedge. The value obtained on a 20-centimeter net calibrated to 2° is 12½° and by trigonometry 12° 21′, using the formula

$$\tan A = \tan Db \sin R \text{ (Fig. 2)}$$

SOLUTIONS FOR PITCH

GENERAL STATEMENT

To prepare a drawing representing relations in a fault plane one must know angular relations of lines on the plane. These lines may be traces on the fault of tabular bodies, such as beds, veins, and dikes, or may be lines produced during fault movement, such as grooves and striations. The angle that can be plotted is pitch (Fig. 2). In many cases pitch cannot be directly measured in the field but can be derived from known strike and dip of bed and fault. Field observations on an exposed fault wall may have been recorded not as pitch, but as plunge or direction of plunge. These must be converted to pitch for plotting in the fault plane.

Pitch can be obtained by three methods: (1) graphically by triangles, (2) by trigonometry, and (3) with the aid of a net. The greatest accuracy is obtained by (2). When computations are performed with five-place logarithmic functions, accuracy is usually much greater than that of field measurements. To check computed results for mistakes, it is advisable to use one of the graphic methods. Of these, the net method is quicker.

PITCH FROM STRIKE AND DIP OF FAULT AND BED

Method of triangles.—Relations in the example (Fig. 4) are essentially those shown in the block diagram (Fig. 2), and points are correspondingly lettered. Sequence of construction of triangles and transfer of distances is indicated in Figure 4.

Trigonometric method.—In order to select the applicable formula for pitch (Fig. 5),

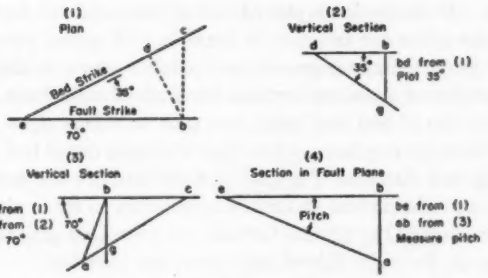


FIGURE 4.—*Pitch from strike and dip of bed and fault by triangles*

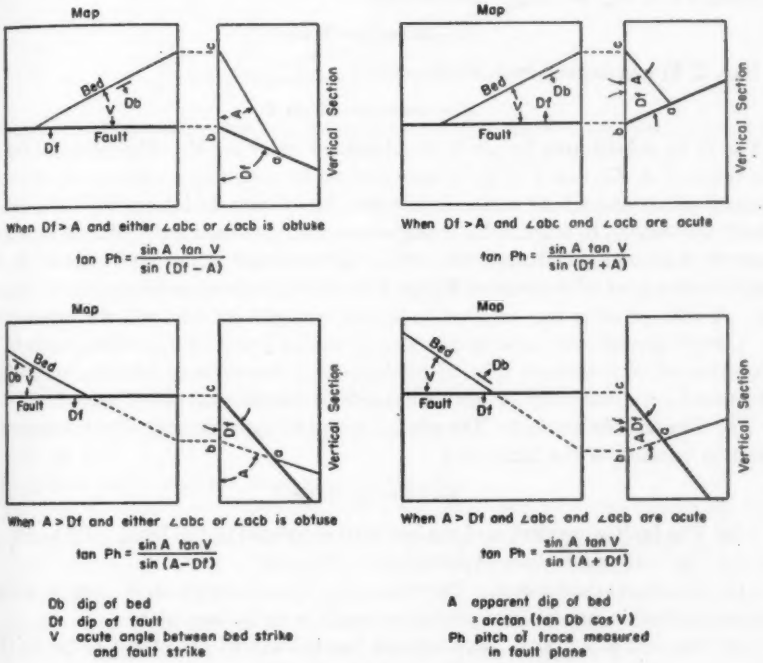

Map
Bed
Db
V
Df
Fault
Vertical Section
When Df > A and either ∠abc or ∠acb is obtuse
tan Ph = sin A tan V / sin (Df − A)
When Df > A and ∠abc and ∠acb are acute
tan Ph = sin A tan V / sin (Df + A)
When A > Df and either ∠abc or ∠acb is obtuse
tan Ph = sin A tan V / sin (A − Df)
When A > Df and ∠abc and ∠acb are acute
tan Ph = sin A tan V / sin (A + Df)
Db dip of bed
Df dip of fault
V acute angle between bed strike and fault strike
A apparent dip of bed = arctan (tan Db cos V)
Ph pitch of trace measured in fault plane

FIGURE 5.—*Pitch from strike and dip of bed and fault by trigonometry*

it is first necessary to compute the apparent dip of bed in a section normal to fault strike, using the formula

$$A = \arctan (\tan Db \cos V)$$

This can be checked for major error by the net method for apparent dip of bed (Fig. 3). Point *a* (Fig. 5) is on the trace below ground, and points *b* and *c* at the

ground surface. If the section is placed so that bed and fault do not intersect below ground, the rules given for selection of formula still apply, provided that point *a* is on the trace projected above ground and points *b* and *c* on the ground surface.

In the derivation of a general formula for pitch of trace from known strike, dip, and direction of dip of bed and fault, two plus or minus signs appear, depending upon whether fault dip is greater or less than apparent dip of bed and whether direction of fault dip and direction of apparent dip of bed are the same or opposed. In order to avoid a mathematical statement as to when to use a plus sign and when a minus, the four cases of the general formula are presented graphically. Two of the formulas, those on the right side of the figure, are identical.

The formula for A in terms of Db and R (Fig. 2) was derived by assigning a value of unity to bd and solving in order, with appropriate substitutions of values, right triangles bcd, bdg, and cbg. The formula

$$A = \arctan (\tan Db \cos V)$$

(Figs. 2, 5) was derived from the formula

$$A = \arctan (\tan Db \sin R)$$

(Fig. 2) by substituting for $\sin R$ its equivalent value $\cos V$. The formulas for Ph in terms of A, Df, and V (Fig. 5) were derived by assigning a value of unity to the map distance along fault strike from right side of map to intersection of bed and fault and solving in order, with appropriate substitutions, a right triangle in a horizontal plane, oblique triangle abc, and a right triangle in the fault plane. In the case of the upper left formula of Figure 5 relations are shown in perspective in Figure 2. A value of unity was assigned to be, and triangles bce, abc, and abe were solved.

Certain special cases arise in which pitch can be found by inspection, or in which substitution in a formula (Fig. 5) produces an indeterminate solution. The symbols used in the following discussion are defined and illustrated in Figure 2.

(a) The fault is vertical. The pitch is equal to apparent dip of bed in a vertical section parallel to the fault, and

$$\tan Ph = \tan Db \sin V$$

(b) The fault is vertical, and the bed strikes normal to the fault. $Ph = Db$

(c) The fault and bed are both vertical. $Ph = 90°$

(d) The fault is horizontal. The term pitch, in the fault plane, of trace of bedding is not applicable, inasmuch as pitch is an angle in an inclined plane.

(e) The bed is vertical. The formula can be derived by letting plane aef (Fig. 2) represent the vertical bed. The angle marked S in the diagram then becomes V, the acute angle between fault strike and bed strike. Derivation of the formula can be carried out by assigning a value of unity to be and solving in succession right triangles bef, abf, and abe.

$$\tan Ph = \frac{\tan V}{\cos Df}$$

(f) The bed is horizontal. $Ph = 0$.

(g) The fault dip and apparent dip of bed are equal and in the same direction. $Ph = 90°$ (Fig. 6)

(h) The fault dip and apparent dip of bed are equal and opposed. This is a special case of relations in Figure 5, with *bc* the base of an isosceles triangle, and the formula reduces to:

$$\tan Ph = \frac{\sin Df \tan V}{\sin 2\,Df}$$

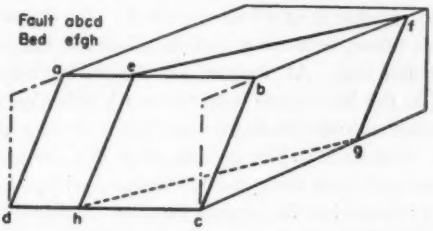


FIGURE 6.—*Fault dip and apparent dip of bed are equal and in the same direction; pitch in fault plane is 90°*

In some fault problems subsequently treated, sections in the plane of a faulted vein are used, and it is necessary to compute pitch of the trace of fault measured in the plane of the vein. The formulas in Figure 5 apply, provided the sketch cross section is drawn normal to vein strike, not fault strike, and terms are redefined as follows:

Db dip of fault

Df dip of vein

V acute angle between vein strike and fault strike

A apparent dip of fault in a vertical section normal to vein strike = *arctan* (*tan Db cos V*)

Ph pitch of fault measured in the plane of the vein

Net method.—The net is described in a previous section. The procedure for obtaining pitch and plunge of the trace of a bed striking N. 70° E. and dipping 30° S. on a fault striking N. 15° E. and dipping 60° E. is illustrated in Figure 7. The net is fixed on a table, and a sheet of tracing paper is placed on it with a needle through the paper and center of the net, so that the tracing paper can be rotated. The periphery of the net is represented by a full line and is considered as lying in a horizontal land surface. All other full lines are on the tracing paper. Dotted lines represent meridians and parallels of the net and should be considered as on the surface of a transparent hemisphere beneath the ground surface.

(1) Strike and dip of fault and bed are plotted, using the circle as a protractor. The north pole is marked by an arrow for reference.

(2) The bed-strike line is rotated onto the polar diameter. Inspection of the dip symbols shows that the line of intersection of bed and fault now lies in the northeastern area closer to the fault-strike line than to the bed-strike line. The intersec-

tion of the bed with the hemispherical surface below ground is the 30-degree meridian on the east side of the bed-strike line. Part of this meridian north of the fault-strike line is traced on the paper.

(3) The fault-strike line is rotated to the polar diameter. The intersection of the fault plane and hemispherical surface below ground is the 60-degree meridian to the east. Point *w* is marked at the intersection of this meridian and the one previously traced on the paper at position (2). A line drawn from the center of the net to *w* is the intersection of bed and fault; it is at the ground surface at the net center and pierces the hemispherical surface at *w* below ground. The desired pitch is the angle, measured in the fault plane, between a horizontal line on the fault and the line of intersection of fault and bed. At position (3) the tracing paper is in position to read this angle, 34°, in the fault plane from the south pole along the meridian to *w*.

(4) Point *w* is rotated onto the 90-degree meridian. It now lies vertically below the polar diameter. Inasmuch as plunge is an angle in a vertical plane, the plunge, 29°, is read from the south pole along the 90-degree meridian to *w*.

(5) The tracing is returned to its original position indicated by the north arrow. Direction of plunge, S. 4° E., the bearing down the intersection of fault and bed, is read by placing a straightedge on net center and *w* and reading the bearing on the periphery.

(6) In several fault problems subsequently treated, sections in the plane of a faulted vein are used, and it is necessary to find pitch, in the plane of the vein, of fault trace. This is analogous to pitch of the trace measured in the plane of the bed (Fig. 7). After point *w* has been located, the tracing is returned to position (2) with bed-strike line at the polar diameter. Pitch of fault, 76°, in the plane of the bed is read from the pole along the meridian of bed dip to point *w*.

The values given above were obtained from a 4-inch net calibrated at 10-degree intervals used for the preparation of the illustration. They are tabulated here with results obtained trigonometrically.

	4-inch net	*Trigonometry*
Pitch in fault plane	34°	34° 01′
Pitch in bedding plane	76°	75° 45′
Plunge	29°	28° 58′
Direction of plunge	S. 4° E.	S. 3° 39′ E.

PITCH FROM PLUNGE AND FAULT STRIKE AND DIP

General statement.—Field notes on linear elements observed on a fault wall may be recorded in terms of fault strike, dip, and direction of dip, plunge of line, and a general statement of direction of pitch of line. Pitch of line can be obtained from these observations by the methods below.

Method of triangles.—Right triangles are drawn in the sequence *aef* (Fig. 2), *abf*, *bfe*, and *abe*, with appropriate plotting of plunge and fault dip and transfer of sides from previously drawn triangles.

Trigonometric method.—The formula below was derived by assigning a value of unity to *af* (Fig. 2), solving triangle *aef* for *ae*, triangle *abf* for *ab*, and substituting these values in the solution of triangle *abe* for pitch.

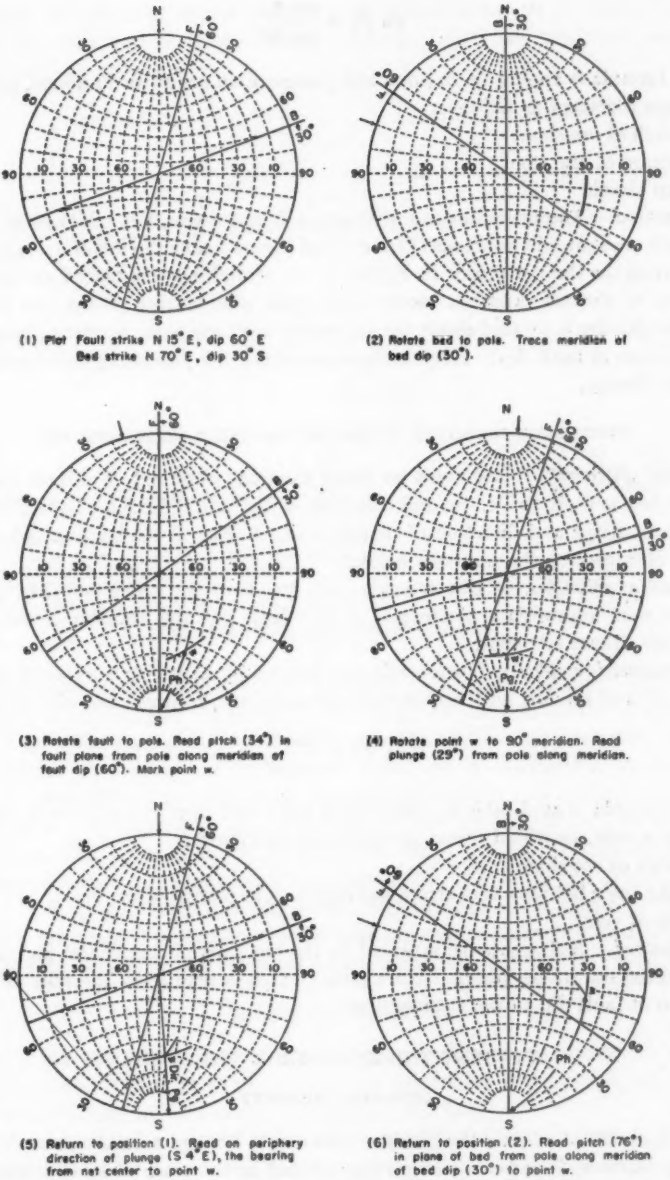

N
S
(1) Plot Fault strike N 15° E, dip 60° E
Bed strike N 70° E, dip 30° S
(2) Rotate bed to pole. Trace meridian of bed dip (30°).
(3) Rotate fault to pole. Read pitch (34°) in fault plane from pole along meridian of fault dip (60°). Mark point w.
(4) Rotate point w to 90° meridian. Read plunge (29°) from pole along meridian.
(5) Return to position (1). Read on periphery direction of plunge (S 4° E), the bearing from net center to point w.
(6) Return to position (2). Read pitch (76°) in plane of bed from pole along meridian of bed dip (30°) to point w.

FIGURE 7.—*Pitch, plunge, and direction of plunge from strike and dip of bed and fault*

$$\sin Ph = \frac{\sin Pg}{\sin Df}$$

This formula is applicable to pitch and plunge of an ore shoot in a vein, provided terms are redefined as follows:

Ph pitch of ore shoot

Pg plunge of ore shoot

Df dip of vein

Net method.—The procedure is not illustrated in a figure, but relations of plunge and pitch are shown in positions (3) and (4) of Figure 7 and the use of a straightedge for rotation on the net center in Figure 3. A straightedge is placed on the polar diameter of the net, and net center and point representing plunge are marked. The straightedge is rotated about the net center until the point marking plunge is on the meridian of fault dip. Pitch is then read from the pole along this meridian to the straightedge.

PITCH FROM DIRECTION OF PLUNGE AND FAULT STRIKE AND DIP

General statement.—Field notes on linear elements observed on a fault wall may be recorded as fault strike, dip and direction of dip, and direction of plunge of line. From fault strike and direction of plunge, angle *S* (Fig. 2) can be obtained. Pitch can be obtained by the methods below.

Method of triangles.—Right triangles are drawn in the order *bef* (Fig. 2), *abf*, and *abe*, with appropriate plotting of *S* and fault dip and transfer of sides from previously drawn triangles.

Trigonometric method.—The formula was derived by assigning a value of unity to *be* (Fig. 2) and solving, with appropriate substitutions, triangles *bef*, *abf*, and *abe*.

$$\tan Ph = \frac{\tan S}{\cos Df}$$

This formula is applicable to relations of pitch and direction of plunge of an ore shoot in a vein, provided terms are redefined as follows:

Ph pitch of ore shoot

S acute angle between vein strike and direction of plunge of ore shoot

Df dip of vein

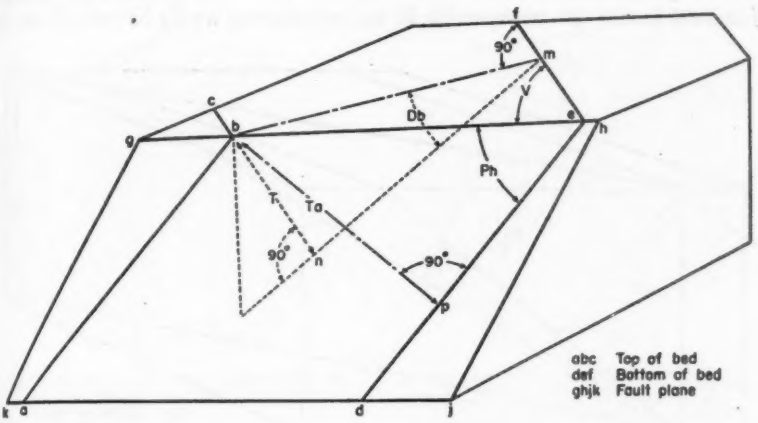
Net method.—A straightedge is placed on the net through the center and at angle *S*, measured on the periphery, from a pole. Pitch is read from the pole along the meridian of fault dip to the straightedge.

APPARENT THICKNESS FROM THICKNESS

GENERAL STATEMENT

The thickness of a bed is the distance from top to bottom normal to stratification. In cross sections, it appears along a line normal to the trace of stratification only where the plane of section is normal to stratification. The term apparent thickness is here used for the distance from top to bottom of bed normal to trace of stratifica-

tion where the plane of section is oblique to stratification, as in vertical sections oblique to strike and in most inclined sections. Apparent thickness is always greater than thickness.



Db Dip of bed
V Acute angle between fault strike and bed strike
Ph Pitch, in fault plane, of trace of bedding
T Thickness of bed
Ta Apparent thickness, in fault plane, of bed

$$Ta = \frac{T \sin Ph}{\sin Db \sin V}$$

FIGURE 8.—*Apparent thickness from thickness*

The methods for deriving apparent thickness from known thickness given below were evolved primarily for the purpose of drawing in inclined faults cutting obliquely across folds. They are of use, however, for drawing vertical sections across plunging folds and for converting known apparent thickness to thickness in stratigraphic work. Commonly the best exposures are along the sides of valleys cutting obliquely across strike. If thicknesses of beds are to be determined by a traverse oblique to strike, measuring slope distances by pacing or chain and plotting apparent dip in the vertical section, apparent thickness is obtained. Similarly the "step" method (Lahee, 1941, p. 425–426) with the Brunton clinometer set at apparent dip gives apparent thickness. It can be quickly and accurately converted to thickness in the field with the aid of a quadrant of a meridional stereographic or Postel net.

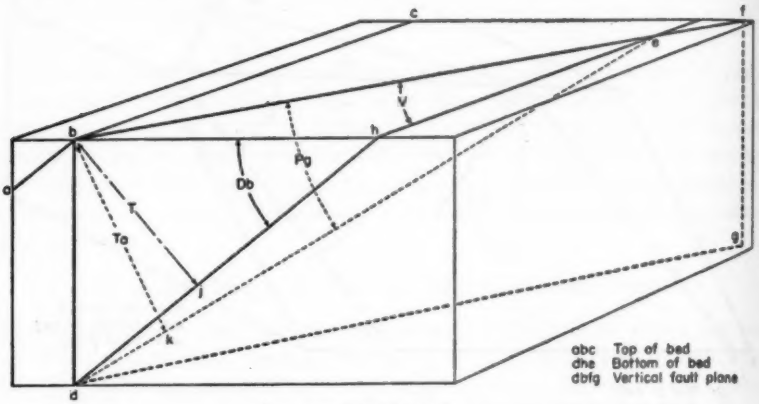
TRIGONOMETRIC METHOD

The general case of apparent thickness on an inclined fault oblique to strike of beds is shown in Figure 8. The formula was derived by the solution, with appropriate substitutions, of right triangles *bmn*, *bem*, and *bep*.

The special case of a vertical fault oblique to strike of beds is given in Figure 9. Inasmuch as the fault plane is vertical, the angle in the fault plane between horizontal and trace of stratification is plunge, not pitch. If vertical plane *bfgd* is considered as the plane of a vertical section, angle *Pg* is apparent dip.

Formula (1) on Figure 9 was derived by the solution, with appropriate substitutions, of right triangles *bdh*, *beh*, and *bde*.

In right triangle *dbj*, angle *dbj* is equal to *Db*; in right triangle *dbk*, angle *dbk* is equal to *Pg*. Formulas (2) and (3) were derived by the solution of right triangles *dbj* and *dbk* having the common side *bd* and substituting for *Pg* its value from (1).



Db Dip of bed
V Acute angle between fault strike and bed strike
Pg Plunge of trace of bedding
T Thickness of bed
To Apparent thickness, in fault plane, of bed

(1) $\tan Pg = \tan Db \sin V$

(2) $To = \frac{T \cos Pg}{\cos Db} = \frac{T \cos [\arctan (\tan Db \sin V)]}{\cos Db}$

(3) $T = \frac{To \cos Db}{\cos Pg} = \frac{To \cos Db}{\cos [\arctan (\tan Db \sin V)]}$

(4) $To = \frac{T \sin Pg}{\sin Db \sin V}$

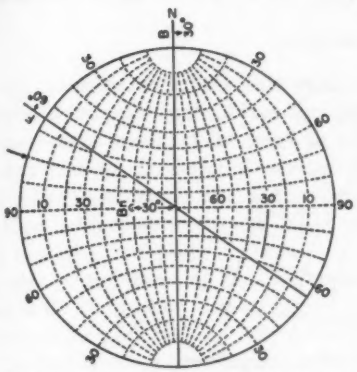
FIGURE 9.—*Apparent thickness from thickness; fault is vertical*

Formula (4) was derived by the solution, with appropriate substitutions, of right triangles *bhj*, *beh*, and *bek*. It is identical with that in Figure 8 except for the use of *Pg* instead of *Ph* to designate the angle in the fault plane between horizontal and trace of stratification. Formula (4) is not recommended for use.

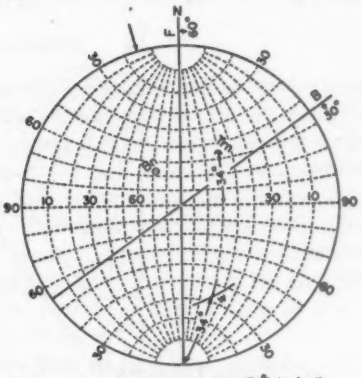
NET METHOD

The fault and bed (Fig. 10) are those whose strikes and dips are plotted in (1) of Figure 7. At position (2) of Figure 10, in addition to tracing part of the meridian 30°, point *Bn* is marked on the equatorial diameter 30° from net center opposite the direction of dip of bed. A line from net center to *Bn* plunges 60° due west and is consequently a bedding normal or line normal to stratification. At position (3) with the fault on the polar diameter, part of the meridian 60° in the direction of dip of fault is traced, locating point *w*, the intersection of bed, fault, and hemispherical surface below ground. A line from net center to *w* is the trace of the bed on the fault. Its pitch in the fault plane, 34°, is read from the south pole along the meridian 60° to *w*. The angle 34° is laid off from the equator into the adjacent quadrant along the meridian 60°, locating point *Trn*. The angle in the fault plane between a line

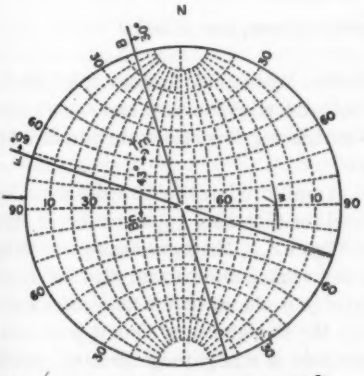
from net center to *w* and a line from net center to *Trn* is 90°. The line from net center to *Trn* is consequently a trace normal, or line on the fault plane normal to trace on the fault plane of stratification. Point *w* is rotated to the equatorial diameter (7).



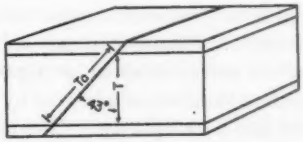
(2) Rotate bed to pole. Trace meridian of bed dip. Plot point Bn 30° from center along equator opposite direction of dip.



(3) Rotate fault to pole. Read pitch (34°) in fault plane from pole along meridian of fault dip (60°). Mark point w. Plot point Trn 34° from equator along meridian 60° on opposite side of equator from w.



(7) Rotate point w to equator. Read angle (43°) between points Bn and Trn.



(8) Beds restored to horizontal and cut by fault at 43° from thickness.

T Thickness
To Apparent thickness in fault plane

$$To = \frac{T}{\cos 43°}$$

FIGURE 10.—*Apparent thickness from thickness*

If the work so far is correct, both *Bn* and *Trn* lie on the meridian 61°, which is the complement of the plunge, 29°, of the trace of stratification on the fault read from the periphery along the equator to *w*. The angle 43° between points *Bn* and *Trn* is the angle between a line normal to stratification and a line on the fault normal to trace of stratification. This relation is shown in (8). Apparent thickness can be obtained from known thickness by drawing to scale the triangle on the front of the block or by use of the formula. In some cases the angle read on the net between *Trn*

and *Bn* is greater than 90°. The acute angle between trace normal and bedding normal is 180° minus this angle.

From known thickness of 1000 feet for the bed in the example above, the net method gives an apparent thickness of 1367 feet. Computed apparent thickness,

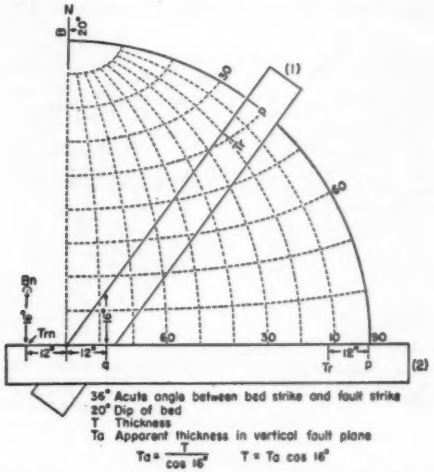


FIGURE 11.—*Apparent thickness from thickness; fault is vertical*

using the formulas in Figures 5 and 8 and 5-place logarithmic functions, is 1366 feet. A number of problems worked both by net and trigonometry show that values for apparent thickness obtained with a 20-centimeter Postel net are within 0.3 per cent of the values obtained by trigonometry.

Apparent thickness of a bed cut by a vertical fault can be obtained with a quadrant of a net and a straightedge. The net method for obtaining apparent dip or plunge of trace of bed on a vertical fault is given in Figure 3. The same example is treated for apparent thickness in Figure 11. The bed strikes due N. and dips 20° E.; the vertical fault strikes N. 36° E. The straightedge is placed on the net center and 36° at the periphery (1). A line is drawn along the straightedge. Point *p* is marked at the periphery, and point *Tr* at the intersection of straightedge and the meridian 20°. A line from net center to *Tr* is the trace of the bed on the fault. The straightedge is rotated on the net center to position (2). Plunge of trace, 12°, is read along the equator between *p* and *Tr*. Point *q* is plotted 12° from net center. The angle 16°, read from *q* along the meridian 78° to the line drawn on the net at position (1), is the angle between a line normal to stratification and a line on the fault normal to trace of stratification. Apparent thickness can be obtained from known thickness, the angle 16°, and the trigonometric formula, or a triangle drawn as in (8) of Figure 10.

Tracing paper was placed on the net, and the problem was performed by the method in Figure 10. With point *Tr* (Fig. 11) on the equator, points *Bn* and *Trn* are at the positions shown to the left of the net quadrant, providing justification for the straightedge method.

A thickness of 1000 feet was assigned to the bed. The net method gave an apparent thickness of 1040 feet, and the trigonometric method (Fig. 9) 1039 feet.

EXAMPLES

GENERAL STATEMENT

The examples treated are mainly faults for which graphic solutions involve a maze of lines, if the usual types of drawings, plan and vertical cross section, are used. The characteristic feature of the solutions here presented is the employment of sections in fault planes. Evidence of movement on a fault, such as faulting out, repetition, and offset of tabular bodies, is the result of amount and direction of movement on the fault with respect to traces on the fault of tabular bodies; consequently a drawing to scale in the plane of the fault is the most satisfactory means of illustration. In addition to presenting what is known about the fault, a section in the fault plane may make it apparent that additional data are necessary for a solution or that the field data for a solution probably cannot be obtained.

The sections in planes of veins and faults may at first seem confusing to one accustomed to vertical sections, for which the reader's line of vision is horizontal. The inclined sections are oriented to follow the usual convention requiring the reader to change his line of vision 90° or less from north. This results, however, in line of vision inclined downward in some cases and upward in others. For example, in reading section *af* (Fig. 14) the line of vision is on bearing N. 17° W. and 22° below horizontal and for section *gd* on bearing N. 64° W. and 38° above horizontal.

Black lines, such as full, dashed, and dotted, are used in the sections to represent different features such as traces of planes, grooves, and construction lines. Legibility of section can be considerably improved by use of color, such as one color for traces of planes in the near block, another for traces of planes in the far block, and a third for construction lines.

The maps presented deal with outcrops on a horizontal surface. If relief has an appreciable effect on outcrop, it is advisable to revise the map before drawing sections so that the pertinent features represent relations as they would appear cropping out on a horizontal surface.

No attempt has been made in the examples to take into consideration drag in the vicinity of the fault, and it is assumed that observations from which pitch angles are derived were made outside the drag zone. In the case of a faulted bed exposed at the surface and with strike different from that of the fault, drag can be taken into consideration by deriving pitch from strike and dip outside the drag zone and drawing the trace on the fault through the point at the surface where the bed is in contact with the fault.

TRANSLATORY OBLIQUE FAULT CUTTING A VEIN

The two parts of the vein in the map (Fig. 12) have the same strike and dip, and the fault consequently appears to be translatory. Grooves or striations on the fault wall plunging N. 76° E. indicate that the last movement was in this direction. Possibly there were earlier movements on the fault in other directions; the problem of locating the ore shoot in the north block is subject to this uncertainty.

To draw the sections in the fault plane and plane of the vein, the angles below were derived from observed angles. Net readings were estimated to the nearest 20 minutes. Trigonometric computations were made with 5-place logarithmic functions to the nearest minute.

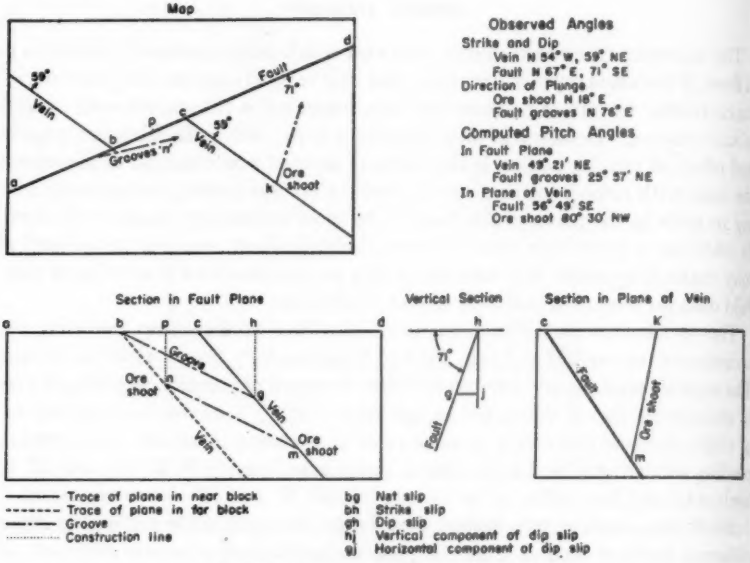


FIGURE 12.—*Faulted vein and ore shoot*

PITCH ANGLES

	20-cm. net	*Computed*
IN FAULT PLANE		
Vein	49° 20′	49° 21′
Grooves	26° 20′	25° 57′
IN PLANE OF VEIN		
Fault	56° 40′	56° 49′
Ore shoot	80° 40′	80° 30′

In the fault-plane section, points *b* and *g* were in contact before faulting, provided the last movement on the fault was in the same direction as earlier movements. Line *hg* is drawn in the direction of dip of fault. Distance *bg* is net slip, *hg* dip slip, and *bh* strike slip (Fig. 1). The vertical section in the direction of dip of fault (Fig. 12) is drawn to resolve dip slip into its vertical and horizontal components *hj* and *gj*. Fault movement can then be expressed in terms of vertical component and horizontal components respectively parallel and normal to fault strike.

To estimate the accuracy of the net and graphic method the map and sections were drawn on a scale of 1 inch = 1000 feet with distance *bc* 1000 feet. The angles from the 20-centimeter net were plotted with a drafting machine accurate to 10

minutes. The computed values of net slip and components were obtained from the distance *bc* of 1000 feet, the computed angles above, and the solution of one oblique and two right triangles with 5-place logarithmic functions.

Distance	Net and graphic (feet)	Computed (feet)	Per cent error
Net slip	1930	1911	1.0
Strike slip	1730	1718	0.7
Dip slip	850	836	1.7
Vertical component of dip slip	810	790	2.5
Horizontal component of dip slip	270	272	0.7

The section in the plane of the vein was drawn to locate *m*, the intersection of fault and ore shoot in the south block. Distance *cm* along the intersection of fault and vein was transferred to the fault-plane section, locating the ore shoot in the south block in this section. Line *mn*, drawn parallel to *bg*, locates the intersection of fault and ore shoot in the north block. The location of *n* with respect to *m* can be expressed in terms of distance *mn* and pitch of this line or in terms of various directions and rectangular components of net slip. In the case of this faulted ore body, it would seem more economical to start new mine workings from the surface rather than to extend old ones. In order to locate *n'*, a point on the surface vertically above *n*, line *pn* is drawn, and *p* is transferred to the map. From here *n'* is S. 23° E. a distance of $np \cos 71°$, and depth *nn'* is $np \sin 71°$. These computations can be checked by a vertical section including *np*. Direction of plunge of ore shoot north from *n* is the same as in the south block, inasmuch as the vein has not been rotated. If plunge is desired for mapping in the north block, it can be obtained from known angles of vein and ore shoot by methods previously discussed.

OBLIQUE FAULT CUTTING A SEAM

A faulted seam, such as coal or bedded iron ore, is presented by structural contour map (Fig. 13), inasmuch as field data are likely to be assembled in this form. The fault seems to be rotatory (Reid *et al.*, 1913, p. 167), in that strike and dip of beds change abruptly at the fault. Cursory examination of the map suggests that the fault is a pivotal, scissors, or rotational fault (Lahee, 1941, p. 215), with the pivot point located at the trace of the seam on the fault at approximately 1500 feet elevation. Examination of the section in the fault plane shows that relations could have been produced (1) by a rotation of 10° on an axis normal to and intersecting the fault plane at *m*, (2) by a rotation of 10° on an axis normal to the fault plane at some other place, plus a translatory movement to bring the edges of the seam to their present positions, or (3) by purely translatory movement of one block from another part of a plunging fold, where strike and dip differ. Probably many faults have been called pivotal, scissors, or rotational, and location of pivot stated on the basis of relations shown on a map or sections across the fault. A section in the fault plane is likely to present additional hypotheses as to movement, and these should be included among the multiple hypotheses until evidence appears that justifies rejection. For purposes of mining the seam, the question of what movements produced the observed relations is not pertinent, except insofar as the distance along the fault

between points in contact before faulting may have involved facies changes and consequent differences in quality and thickness of seam across the fault.

Standard methods for obtaining strike and dip from a structural contour map give the following:

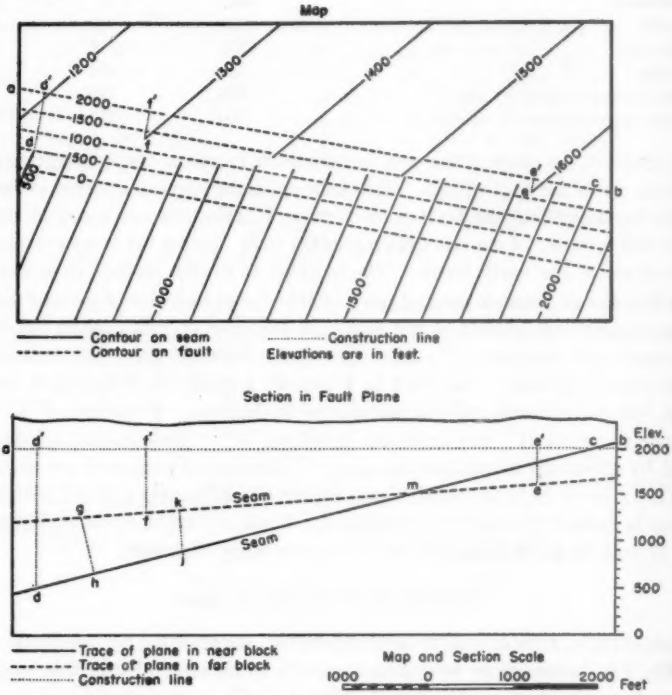


FIGURE 13.—*Faulted seam*

	Strike	*Dip*
Fault	N. 80° W.	65° S.
Beds in north block	N. 50° E.	5° NW.
Beds in south block	N. 23° E.	13° 30′ NW.

Pitch of trace of seam was obtained graphically as described below. This was done at approximately twice the size of the illustration (Fig. 13), and angles were measured by a drafting machine protractor accurate to 10 minutes. Graphic and computed results are as follows:

	Graphic pitch	*Computed pitch*
Trace of seam in north block	4°	4° 8′
Trace of seam in south block	14°	14° 6′

The 2000-foot contour on the fault was used as the datum line for drawing the section. The scale for elevations on the fault plane is not the scale of distances on

the section; it can be prepared by drawing a vertical section normal to fault strike, or preparing a scale equal to the map scale divided by the sine of fault dip. Trace of the seam in the near block was drawn as follows: Point *c* was transferred from map to section at 2000 feet elevation, locating one point on the trace. Point *d* on the map was projected normal to fault strike to *d'* on the 2000-foot contour; *d'* was transferred to the 2000-foot contour on the section. Point *d* on the section was located on the dip line through *d'* at 500 feet elevation. Points *c* and *d* locate the trace of the seam in the near block. Trace of the seam in the far block was drawn by the same method, using *f*, *f'*, *e*, and *e'*.

Mine workings at *m* can be extended across the fault without running out of the seam. At other places the shortest distance from edge to edge of disrupted seam is the perpendicular slip (Fig. 1), the component of slip at right angles to the trace of the seam (Reid *et al.*, 1913, p. 170). If the seam traces are not parallel, perpendicular slip should be understood to mean the distance along a line on the fault perpendicular to the trace in the other block. For instance, if mine workings in the north block (Fig. 13) encounter the fault at *g*, the shortest distance to the seam in the south block is along *gh*, a line on the fault perpendicular to the trace in the south block. Conversely, if mine workings in the south block encounter the fault at *j*, the shortest distance to the seam in the north block is along *jk*, a line perpendicular to the trace in the north block. Length and pitch of perpendicular line appear on the section. If plunge and direction of plunge of line are desired, they can be obtained from pitch and fault strike and dip by methods previously discussed.

ROTATORY FAULT CUTTING INTERSECTING VEIN AND DIKE

The vein and dike in the map (Fig. 14) maintain constant strike and dip within a fault block but change strike and dip abruptly at the fault. The fault movement was, therefore, fairly certainly rotatory, or one in which "some straight lines on opposite sides of the fault and outside the dislocated zone, parallel before the displacements, are no longer parallel afterward" (Reid *et al.*, 1913, p. 167).

Pitch angles for the sections are as follows:

	20-cm. net	*Computed*
IN FAULT PLANE		
Dike in north block	48° 30′	48° 27′
Dike in south block	63° 30′	63° 30′
DIFFERENCE	15° 00′	15° 03′
Vein in north block	51° 40′	51° 45′
Vein in south block	37° 00′	36° 44′
DIFFERENCE	14° 40′	15° 01′
IN PLANE OF VEIN		
Fault	45° 00′	44° 44′

The sections in the fault plane and plane of vein were drawn, and distance *dh* transferred from vein section to fault section, thus locating *h*, the intersection of

fault and ore shoot in the south block. Net slip, "the distance, measured on the fault surface, between two formerly adjacent points situated, respectively, on opposite walls of the fault" (Reid *et al.*, 1913, p. 170), for the intersection of dike and vein is distance *jk*. From here surfaceward between the vein traces, net slip decreases

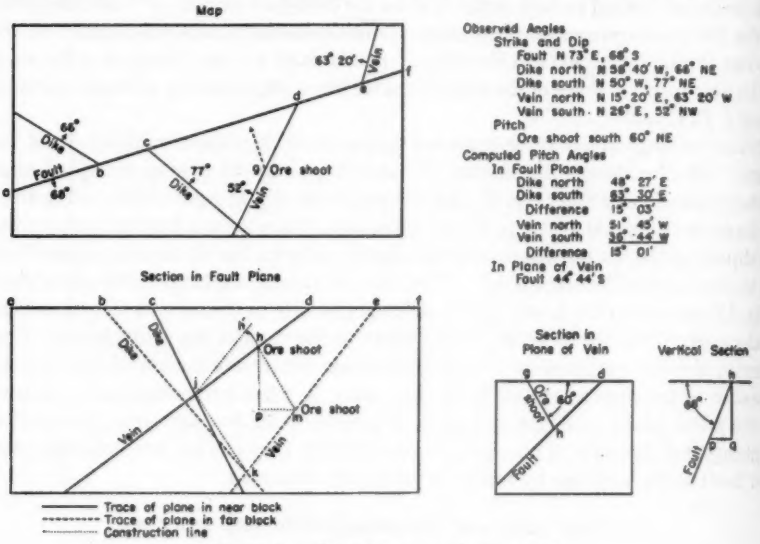

Map
Vein
Dike
Fault
Ore shoot
Observed Angles
Strike and Dip
Fault N 73° E, 68° S
Dike north N 38° 40' W, 66° NE
Dike south N 50° W, 77° NE
Vein north N 15° 20' E, 63° 20' W
Vein south N 26° E, 52° NW
Pitch
Ore shoot south 60° NE
Computed Pitch Angles
In Fault Plane
Dike north 48° 27' E
Dike south 63° 30' E
Difference 15° 03'
Vein north 51° 45' W
Vein south 36° 44' W
Difference 15° 01'
In Plane of Vein
Fault 44° 44' S
Section in Fault Plane
Section in Plane of Vein
Vertical Section
Trace of plane in near block
Trace of plane in far block
Construction line

FIGURE 14.—*Faulted vein, ore shoot, and dike*

and is zero at a "pivot point" somewhere in the vicinity of the intersection of vein traces above ground. It is not necessary to locate this point, as the observed relations could have been produced (1) by a rotation of 15° on an axis normal to the fault plane at the "pivot point," or (2) by a rotation of 15° on a parallel axis intersecting the fault plane elsewhere, plus translatory movement of the proper amount and direction to bring the tabular bodies to their present relative positions. Observations on wall grooves and striations would be of doubtful value in determining direction of movement, inasmuch as they would likely show only the direction of the last movement. In order to find the intersection of fault and ore shoot in the north block, movement can be conveniently considered as consisting of translatory movement of the south block from *k* to *j* followed by a 15-degree rotation of the south block, clockwise as seen looking at the fault plane section, on a line normal to the fault plane at *j*. On the basis of this hypothesis, point *h* was rotated 15° counterclockwise with *j* as a center, to *h'*. Line *h'm* was drawn parallel to *jk*, thus locating *m*, the intersection of fault and ore shoot in the north block. Line *h'm* is omitted from the drawing because it falls close to line *hm* and obscures relations subsequently discussed.

As a check of the method of locating *m*, other points on the fault were arbitrarily chosen for rotation. For instance, *d* was used as a center, and *h* and *j* were rotated 15° counterclockwise respectively to *h''* and *j'* (not shown on the section). Line

$h''m$ was then drawn parallel to $j'k$. Point m fell at the same location on the trace of the vein in the north block.

For the ore shoot, net slip and its components are:

hm net slip
mp strike-slip
hp dip slip
pq horizontal component of dip slip
hq vertical component of dip slip

If vertical and horizontal angles between the ends of the ore shoot at the fault are desired, they can be obtained by methods previously discussed from pitch of line hm and strike and dip of fault.

Inasmuch as the vein has been rotated on the fault plane, pitch of the ore shoot in the north block differs from pitch in the south block. The writer has not attempted a trigonometric solution for pitch in the north block; it probably involves spherical triangles and consequently would be of use to few geologists. Pitch, plunge, and direction of plunge of the ore shoot in the north block can be obtained with the net.

A rotation on an inclined fault plane can be resolved into horizontal and vertical angular components. Let Ph (Fig. 2) represent the angle of rotation on the fault plane; the horizontal and vertical angular components are S and Pg. Formulas appearing in previous sections are:

$$\sin Ph = \frac{\sin Pg}{\sin Df}$$

$$\tan Ph = \frac{\tan S}{\cos Df}$$

Substitution of the value of 15° for Ph and 68° for Df gives a horizontal rotation of 5° 44′ and a vertical rotation of 13° 53′.

The resolution can also be made with the net (Fig. 15). Point p is marked on the meridian 68° at 15° from the pole. The angle in the fault plane between the polar diameter, which represents a horizontal line on the fault, and a line on the fault from net center at the ground surface to p below ground is 15°, the rotation on the fault plane. A line is drawn from net center through p to the periphery. The horizontal rotation, 6°, is read from north on the periphery. Point p is rotated about the net center to the polar diameter. The angle of 14° from the pole to p' is vertical rotation. The operation can be performed with a straightedge, as in Figure 3.

The net (Fig. 16) is in position with the plane of the periphery horizontal and the spherical surface below ground. On a sheet of tracing paper rotating on the net center, strike and dip of vein and fault are plotted (1). The vein in the south block is represented by V, the vein after a horizontal rotation of 5° 44′ in the direction required by relations on the fault by V', and the vein in the north block by V''. It is understood that at all positions the ore shoot emerges at the land surface at the net center. Line V' is moved to the pole (2). The pitch of 60° for the ore shoot in

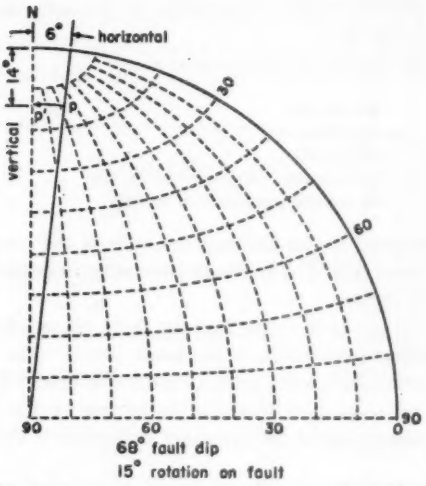


FIGURE 15.—*Resolution of rotation on a fault into vertical and horizontal rotations*

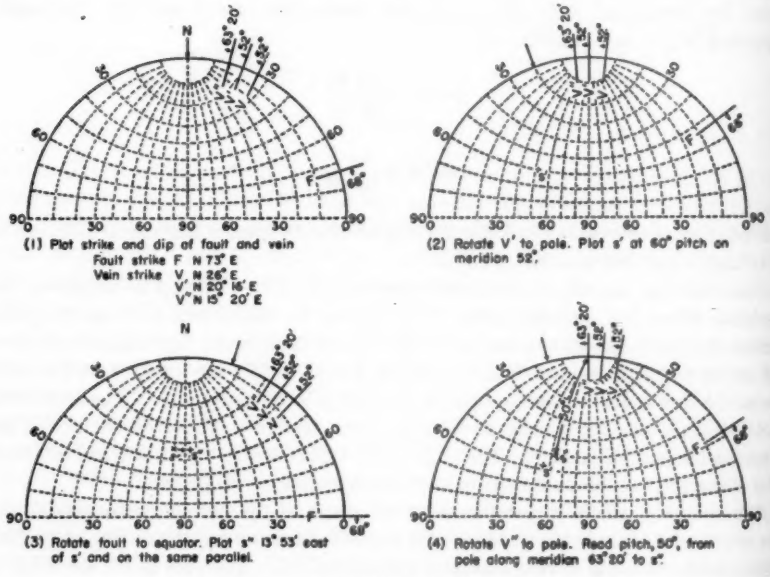

(1) Plot strike and dip of fault and vein
Fault strike F N 73° E
Vein strike V, N 26° E
V' N 20° 16' E
V'' N 15° 20' E
(2) Rotate V' to pole. Plot s' at 60° pitch on meridian 52°.
(3) Rotate fault to equator. Plot s'' 13° 53' east of s' and on the same parallel.
(4) Rotate V'' to pole. Read pitch, 50°, from pole along meridian 63° 20' to s''.

FIGURE 16.—*Pitch of rotated ore shoot*

the south block is plotted from the pole on the meridian 52° representing vein dip, locating the point s' where the ore shoot pierces the spherical surface for strike and dip V'. Position V might have been used in the same manner to plot s, but the

subsequently required horizontal rotation of 5° 44′ would have brought s to the position of s'. It is more convenient to plot s' directly with V' at the pole. The fault line is moved to the equatorial diameter (3). The vein is now to be rotated in a vertical plane 13° 53′ counterclockwise as seen looking horizontally north. During this rotation point s' would move east along a small circle represented by a parallel. Point s'' is consequently plotted 13° 53′ east of s' on the parallel passing through s'. Line V'' is moved to the pole (4). If the work so far is correct, s'' should lie on the meridian 63° 20′. Pitch of ore shoot in the north block is read from the pole along this meridian to s''. The 4-inch net used in preparation of the illustration gave a pitch of 50°. A 20-centimeter net gave 50° 30′. If plunge and direction of plunge of ore shoot in the north block are desired, they can be read from the tracing paper and net by methods previously described.

TRANSVERSE FAULTS CUTTING FOLDS

General statement.—At first glance, it might appear that a simple method for sectioning in an inclined fault plane crossing the axial plane of a fold, such as the one in Figure 19, would be to make a structural contour map from the surface map and then section in the fault plane by methods previously described (Fig. 13). In preparing a structural contour map from surface data, however, the assumption is made that depth is equal to thickness divided by the cosine of the surface dip. At many places in sharp unsymmetric folds, dip varies markedly with depth. The mathematical assumption consequently may introduce serious errors and, where beds are vertical or overturned, is not applicable. For folds with low dips of beds a structural contour map from surface data may be accurate enough for sectioning in an inclined fault. The best type of map is one structurally contoured from adequate subsurface data.

For general use in drawing, from surface maps, sections in inclined fault planes cutting across sharp folds it seems advisable to use a method similar to that for drawing vertical sections normal to trend of sharp nonplunging folds. Instead of dip and thickness in the vertical section, pitch and apparent thickness appear in the inclined section. A difference, however, is that apparent thickness varies from place to place in the section depending upon pitch, bed dip, and angle between fault strike and bed strike (Fig. 8). This variation can be cared for by plotting the appropriate local apparent thickness obtained trigonometrically (Fig. 8) or from the net (Fig. 10). The use of an apparent thickness diagram is discussed below in connection with Figure 19.

A question which arises in sectioning a sharp fold is that of ratio of flank thickness to crestal or trough thickness for the various beds involved. Among the factors producing thickness variation during folding are lithologic differences and consequent differences in competence, depth of burial, and igneous activity in the vicinity. Straley (1938) reached certain conclusions on flank thinning and crestal thickening from pressure-box experiments and gives ratios from several field studies. These are helpful as guides, but judgment as to ratio of flank thickness to crestal or trough thickness must be based on local knowledge of the factors above and any available subsurface data on comparable cases in the vicinity. Inasmuch as thickening and

thinning during folding are not yet subject to exact mathematical treatment, errors in judgment on this point persist in the values of net slip obtained from the section in the fault plane.

It is advisable to prepare the drawing of one fault wall on tracing paper. It can be moved over the drawing of the other wall to find whether bed traces on fault walls can be matched.

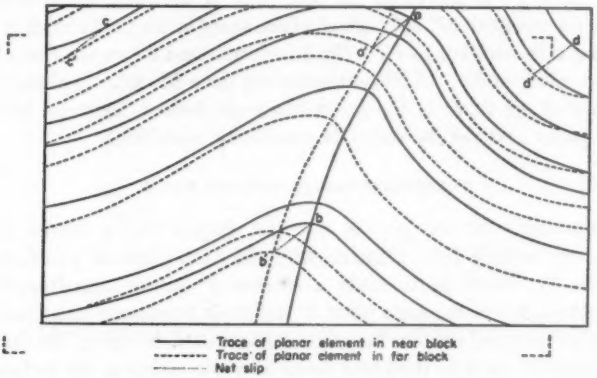


FIGURE 17.—*Section in plane of translatory fault*

Faults crossing matching folds.—A tracing of the full lines (Fig. 17) is prepared and moved until the curved lines on the tracing coincide with the dashed curved lines on the original drawing. The corners of the tracing then fall at the corners indicated on the original by dashed lines. Inasmuch as the edges of the tracing are parallel with those of the original, fault movement is translatory. Net slip is constant and in the same direction for the part of the fault included in the section. It is shown in several places by dotted lines and can be plotted elsewhere by drawing lines parallel and equal to *aa'*.

A tracing of the full lines (Fig. 18), when moved so that curved lines on the tracing coincide with the curved dashed lines on the original, must be rotated and moved diagonally to the position indicated by the dashed corner marks. The tracing can also be brought into coincidence by rotation alone about a point some distance below the lower edge of the drawing and to the left of the center. There is, however, no assurance that relations were produced purely by rotation on this point. The observed results could have been produced by the same angular rotation about some other point plus translation to bring the blocks to their present relative positions.

Net slip varies from place to place and decreases in depth. The near block is upthrown on the left side of the section and downthrown on the right. At *mm'* net slip is nearly parallel to fault strike and at *kk'* nearly parallel to direction of dip of fault. Net slip can be obtained wherever desired in the area of the section by using the tracing to transfer a point on one fault wall to the corresponding position on the other.

Faults crossing nonmatching folds.—The fault (Fig. 19) illustrates some of the

features commonly associated with tear faults. A tracing of beds in a block cannot be moved so that its curved lines coincide with all curved lines of the other. Folding of the beds proceeded, in part at least, with movement on the transverse fault. In addition to rotation of one block with respect to the other on a line normal

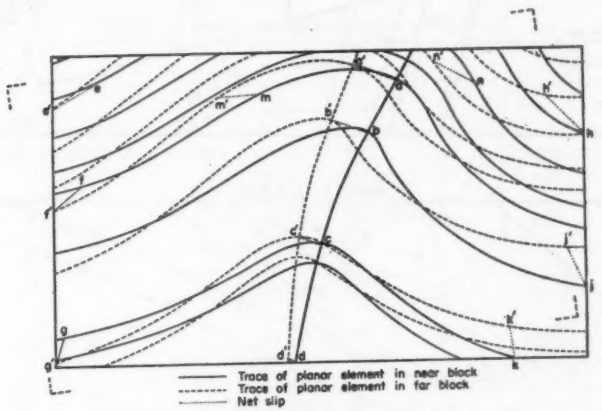


FIGURE 18.—*Section in plane of rotatory fault*

to the fault plane, some lines within a single block, parallel before fault displacement, are not parallel afterward. The fault, nevertheless, is rotatory, as defined by Reid and associates (1913, p. 167).

Both trigonometry and net were used to prepare Table 1 for drawing the section in the fault plane. The angle *Bn-Trn* is the angle between a line normal to bedding and a line on the fault normal to trace of bedding (Fig. 10). Thickness ratio is the ratio of apparent thickness to thickness. The trigonometric value given is from the formula in Figure 8 and the net value from the formula in Figure 10; in both cases a value of unity was assigned to *T*.

The thicknesses in the apparent thickness diagram are considered as having been measured from exposures on the flank of a fold in the vicinity, where beds dip about 30°–60°; they are therefore fairly accurate flank thicknesses for the fold in Figure 19. Beds 1 and 3 are competent sandstones that maintain constant thickness throughout the fold. The other beds are shales for which trough thickness is considered to be 30 per cent greater than flank thickness.

In drawing the section, pitch angles were plotted at the surface. Where the top of bed 3 in the near block dips 28°, pitch is 27° 10′, and angle between bedding normal and trace normal is 27°. The edge of a card was placed on the upper left corner of the apparent thickness diagram and at angle 27°. Apparent thicknesses for beds 1–3 were marked on the edge of the card and transferred to a line on the section normal to the pitch line. The process is analogous to the use of dip and thickness for preparing a vertical section normal to trend of a nonplunging concentric fold. Flank drawing was completed from pitch angles and the corresponding apparent thicknesses. Bisecting the angle between the two pitch lines adjacent to the

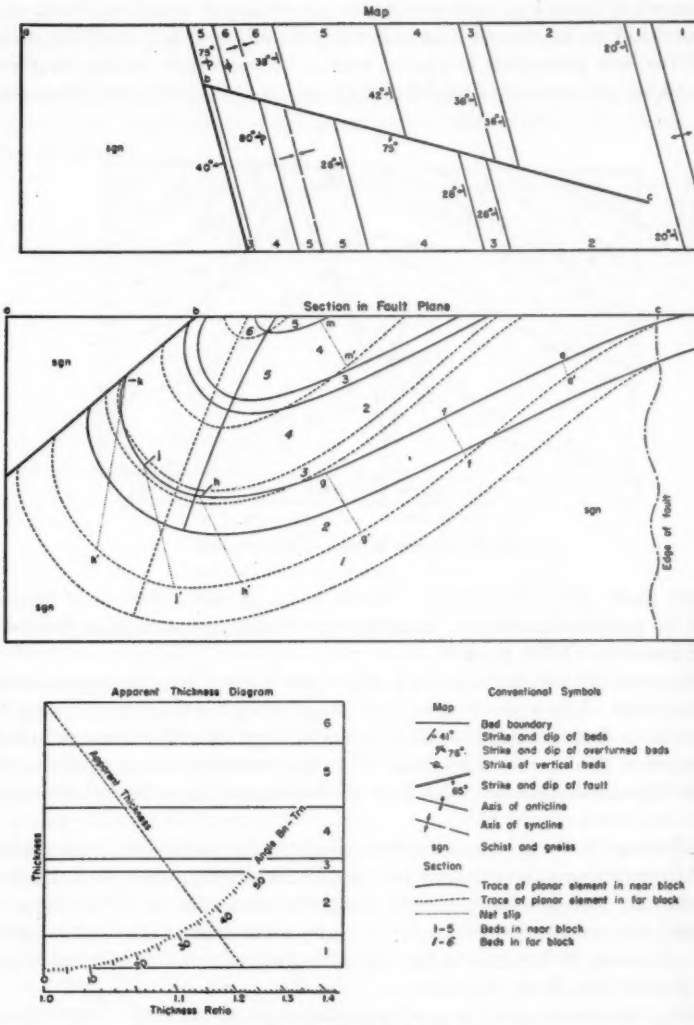


FIGURE 19.—*Rotatory fault*

axial plane at the surface gave an approximate pitch of trace of axial plane on fault of about 70°, and consequently a pitch of about 20° for stratification at the axial plane near the land surface. This pitch corresponds to 24° for angle *Bn-Trn* and 1.095 for thickness ratio. Apparent thicknesses for beds 1 and 3 were taken at 24° on the apparent thickness diagram. The shale beds are considered to have a trough thickness 30 per cent greater than flank thickness. Thickness ratio at the axial

plane is then $1.095 \times 1.3 = 1.43$. The transfer card was placed on the apparent thickness diagram at this ratio to obtain apparent thicknesses for beds 2, 4, and 5 along the axial plane.

TABLE 1.—*Angles and thickness ratios of Figure 19*

	Dip	Pitch		Bn-Trn Net	Thickness ratio		
		Trig.	Net		Trig.	Net	Error (%)
N. block E. to W.	20°	18° 54′	19°	24°	1.094	1.095	0.1
	36°	35° 49′	35° 40′	29° 30′	1.150	1.149	0.1
	38°	38° 02′	38°	30°	1.156	1.155	0.1
	42°	42° 33′	42° 30′	31°	1.167	1.167	0.0
	38°	38° 02′	38°	30°	1.156	1.155	0.1
	0	0	0	15°	.....	1.012	.....
	90°	81° 30′	81° 40′	29°	1.142	1.143	0.1
S. block E. to W.	20°	18° 54′	19°	24°	1.094	1.095	0.1
	26°	25° 04′	25°	26°	1.116	1.113	0.3
	28°	27° 10′	27°	27°	1.123	1.123	0.0
	26°	25° 04′	25°	26°	1.116	1.113	0.3
	0	0	0	15°	.....	1.012	.....
	80°	87° 18′	87°	31° 30′	1.171	1.173	0.2
Thrust fault	40°	40° 18′	40°	.....	.....	.....	.....

A tracing cannot be used on this fault to locate pairs of points on the respective walls in contact before displacement. A dike older than the folding and faulting would be of considerable help in locating pairs of points, but the dike would also be folded and consequently could not be drawn in depth with any degree of certainty. The axial plane of the anticline will serve as a reference datum. Horizontal separation along the fault decreases eastward to *c*, and, inasmuch as along a line from *c* to *d* beds dipping in opposite directions are not offset, it is fairly certain that there is no displacement at the axial plane of the anticline. Points *e* and *e′* were located, with the aid of a chartometer, by measuring off from the axial plane of the anticline equal distances along the respective traces of a bedding plane. Distance *ee′* is net slip at this part of the fault. Net slip, shown elsewhere by dotted lines, varies markedly from place to place on the fault plane both in amount and direction. The straight lines between pairs of points do not indicate, however, the paths travelled by the points to their present respective positions. Undoubtedly the paths were markedly curved, possibly irregularly, on some parts of the fault.

CONCLUSION

(1) A section in the fault plane is a simpler type of drawing than plan and vertical section for treatment of fault problems.

(2) The 20-centimeter net applied to the derivation of angles on inclined planes from angles in vertical and horizontal planes gives results within the limits of error

of most field observations on strike, dip, plunge, and pitch. If the permissible error in field measurements is less than 30 minutes, the trigonometric method is recommended.

(3) Rotatory faults, although fairly common, have not received adequate study. A section in the fault plane provides an approach to study of movement, in that variations in direction and amount of net slip appear in the section.

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UMI

STRATIGRAPHIC COLUMN

COLUMNAR SEC

SECTION	1	2	3	4	5	6	7	8	9	10	11	12
	Calf Creek	Bluff Creek (2B) Mason (2A)	Highway 87 (3C) Camp San Saba (3B) Brady Water Well (3A)	Threadgill Creek	Squaw Creek	Pontotoc	Slick Mountain	Harris Ranch (8B) Salt Branch (8A)	Little Llano River	Carter Ranch	Everett ranch (11B) Point Peak (11A)	Tanyard

CAMBRIAN

WILBERNS FORMATION

Pedernales dolomite member €wp

San Saba limestone member €ws

Point Peak shale member €wpp

Morgan Creek limestone member €wm

Welge sandstone member €ww

Lion Mountain sandstone member €rl.

UPPER

RILEY FORMATION

Cap Mountain limestone member €rc

Hickory sandstone member €rh

PRE—CAMBRIAN

Packsaddle schist, ps; diorite, d; and coarse grained granite, cgr.

SCALE

VERTICAL

200 400 600 800 1000 1200 1400

Bluff Creek section (2B)

Mason section (2A)

Highway 87 section (3C)

Camp San Saba sect. (3B)

San Saba River level

Brady water well (3A)

red brown Brady

Harris ranch section (8B)

Salt Branch section (8A)

fault

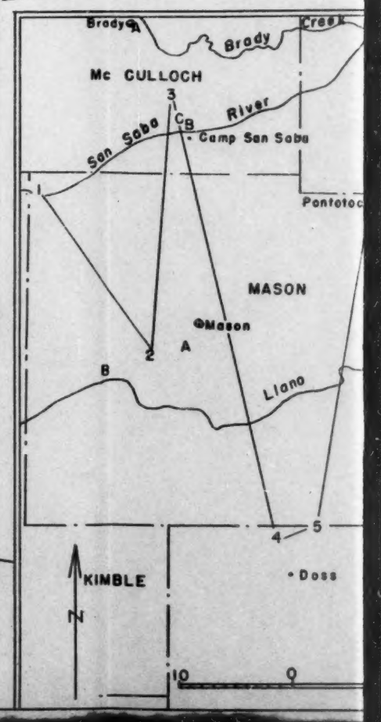
Everett ranch sect. (11B)

Point Peak section (11A)

Plectotrophia zone

Eoorthis zone

El. 1020' Buchanan Lake



EXPLANATION

(Symbolism in columnar sections is only roughly quantitative, and gradation or alternation is indicated by adjacent symbols.)

DOMINANT ROCK

Limestone

- sublithographic
- granular
- dolomitic

Dolomite

- coarse-grained
- medium-grained
- fine-grained
- very fine-grained
- microgranular

Shale

Sandstone

Intraformational conglomerate

Schist

Granite

Diorite

FOSSILS IN THE COLUMNAR SECTIONS

Stromatolitic bioherms more than 8 feet thick

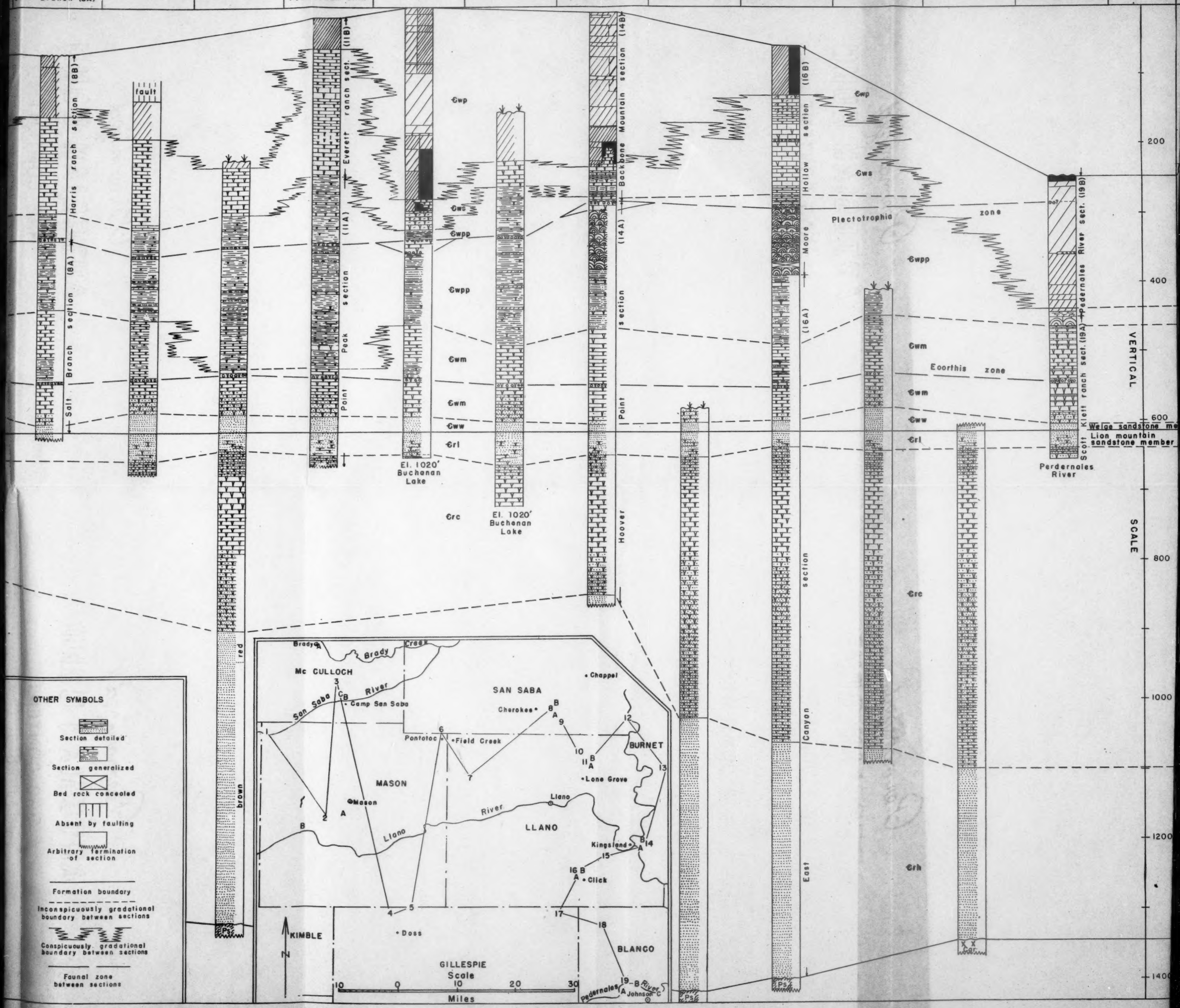
Brachiopods

OTHER SYMBOLS

- Section detailed
- Section generalized
- Bed rock concealed
- Absent by faulting
- Arbitrary termination of section
- Formation boundary
- Inconspicuously gradational boundary between sections
- Conspicuously gradational boundary between sections
- Faunal zone between sections

COLUMNAR SECTIONS

8	9	10	11	12	13	14	15	16	17	18	19	SECTION
Harris Ranch (8B) Salt Branch (8A)	Little Llano River	Carter Ranch	Everett ranch (11B) Point Peak (11A)	Tanyard	Morgan Creek	Backbone Mtn. (14B) Hoover Point (14A)	Packsaddle Mtn.	Moore Hollow (16B) East Canyon (16A)	Cut Off Gap	White Creek	Pedernales R. (19B) Scott Klett ranch (19A)	



OTHER SYMBOLS

- Section detailed
- Section generalized
- Bed rock concealed
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- Arbitrary termination of section
- Formation boundary
- Inconspicuously gradational boundary between sections
- Conspicuously gradational boundary between sections
- Faunal zone between sections

COLUMNAR SECTIONS AND CORRELATION OF THE UPPER CAMBRIAN ROCKS OF CENTR[illegible]

BRIDGE ET AL., PL. 1

STRATI-GRAPHIC COLUMN

UPPER CAMBRIAN — PRE-€.

WILBERNS FORMATION — RILEY FORMATION

San Saba limestone member €ws — Point Peak shale member €wpp — Morgan Creek limestone member €wm — Wilco sandstone member €ww — €rl — Cap Mountain limestone member €rc — Hickory sandstone member €rh — Packsaddle schist, ps; diorite, d; and coarse grained granite cgr.

Pedernales dolomite member €wp

SECTION — 200 — 400 — 600 — 800 — 1000 — 1200 — 1400

VERTICAL SCALE

Lion mountain sandstone member

Scott Kleff ranch sect. (19A) — Pedernales River sect. (19B)

Pedernales River

Plectotrophis zone — Eoorthis zone

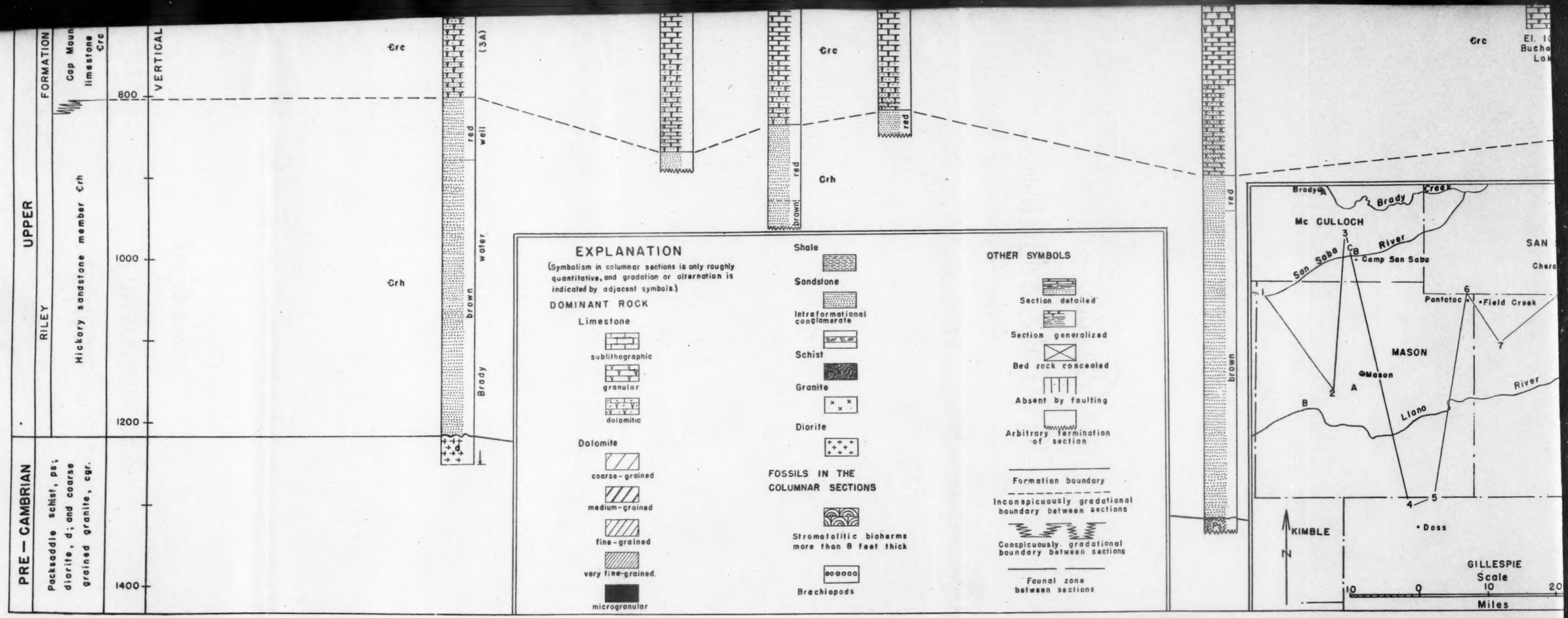
€wp — €ws — €wpp — €wm — €ww — €rl — €rc — €rh

(16B) Moore Hollow section — (16A) Canyon section — East

Backbone Mountain section (14B) — (14A) Point section — Hoover

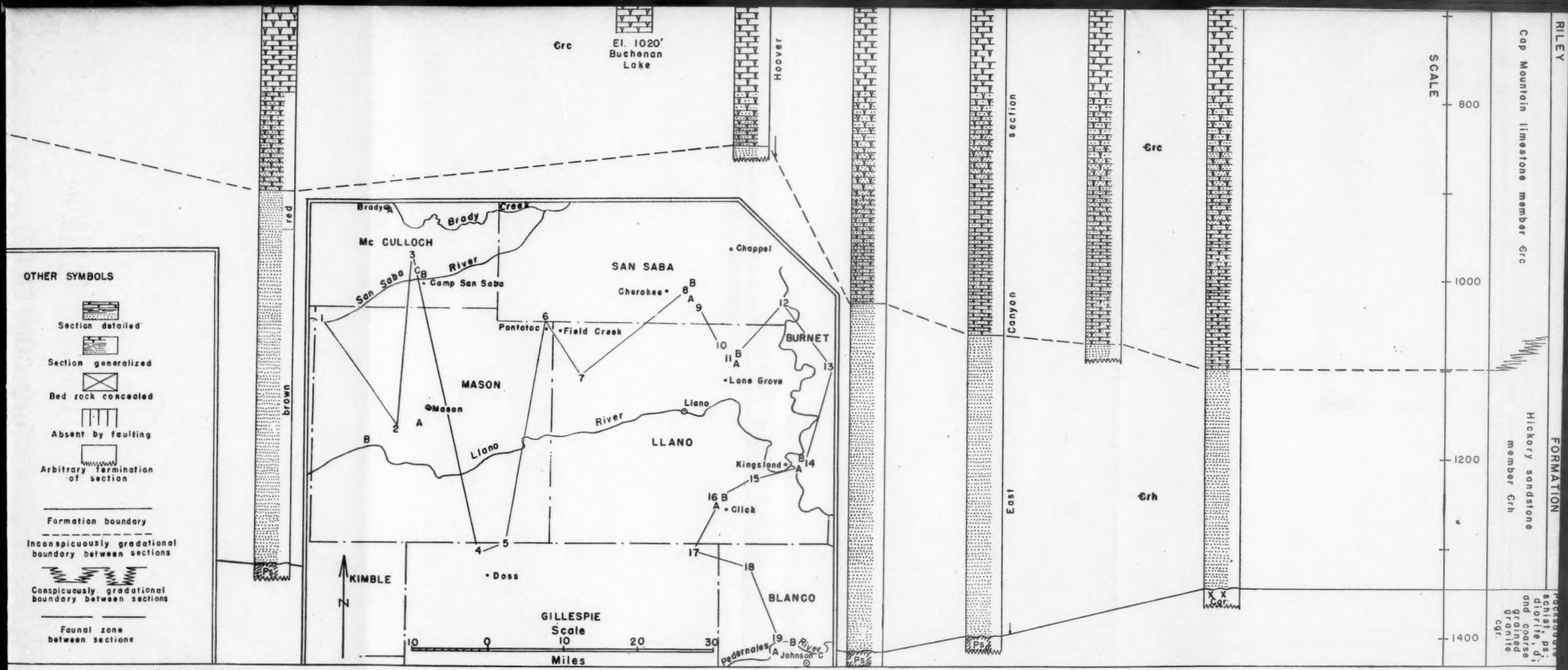
14	15	16	17	18	19
Backbone Mtn. (14B) Hoover Point (14A)	Packsaddle Mtn.	Moore Hollow (16B) East Canyon (16A)	Cut Off Gap	White Creek	Pedernales R. (19B) Scott Kleff ranch (19A)

BURNET — BLANCO — Chappel — Lone Grove — Kingsland — Click — Pedernales (A. Johnson) — 10 11B 11A 12 13 14 15 16B 16A 18 19-B 19-A 30



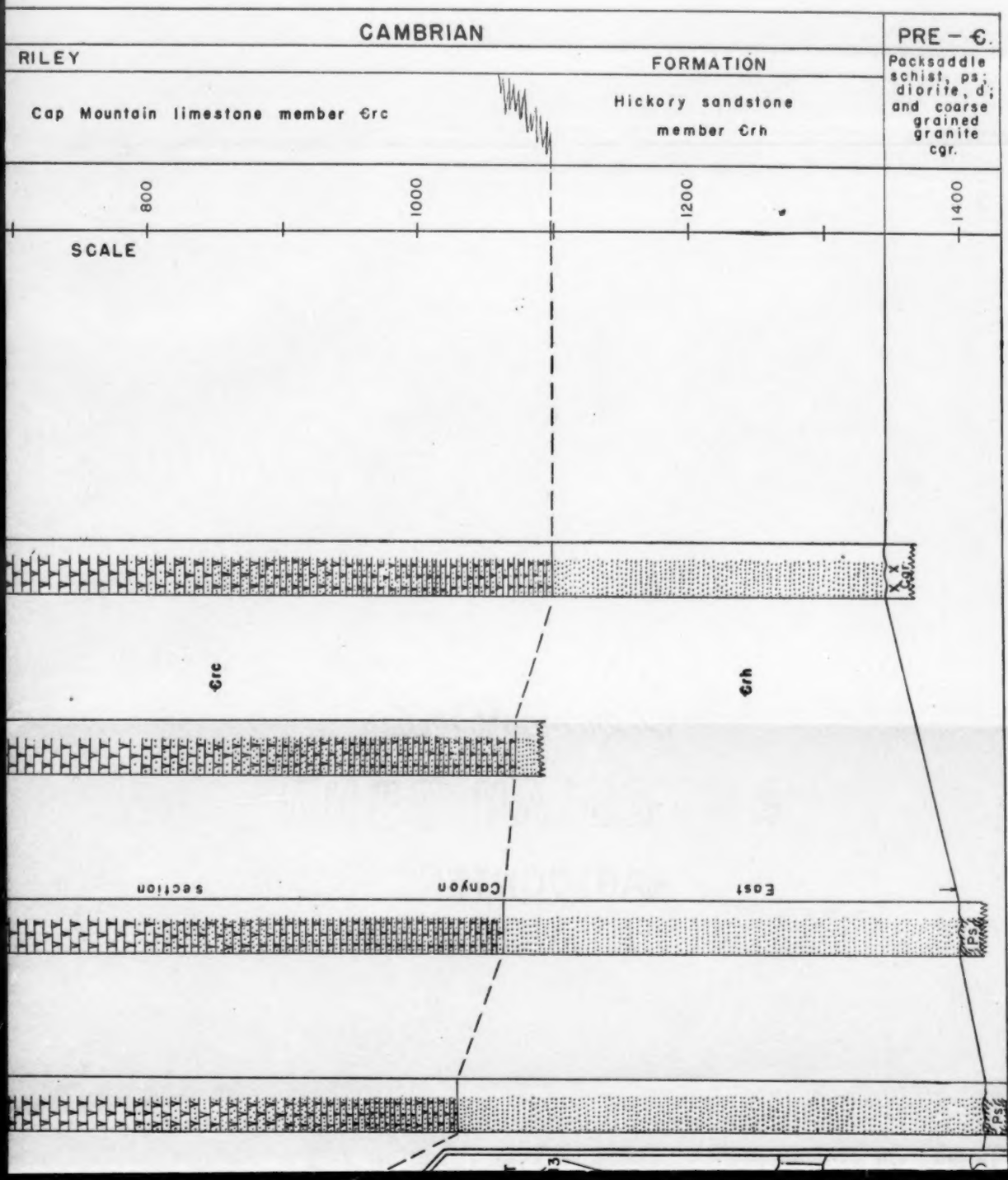
COLUMNAR SECTIONS AND CORRELATION OF THE UPPER CAMBRIAN ROCKS OF CENTRAL TEXAS

Datum is contact of Riley and Wilberns formations



COLUMNAR SECTIONS AND CORRELATION OF THE UPPER CAMBRIAN ROCKS OF CENTRAL TEXAS

Datum is contact of Riley and Wilberns formations


CAMBRIAN
PRE – €.
RILEY
FORMATION
Cap Mountain limestone member €rc
Hickory sandstone member €rh
Packsaddle schist, ps; diorite, d; and coarse grained granite cgr.
800
1000
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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 58, PP. 109-124, 8 PLS. JANUARY 1947

STRATIGRAPHY OF THE UPPER CAMBRIAN, LLANO UPLIFT, TEXAS

BY JOSIAH BRIDGE, VIRGIL E. BARNES, AND PRESTON E. CLOUD, JR.

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ABSTRACT

The two formations and eight members that constitute the Upper Cambrian in the Llano uplift of central Texas are described or redefined, and their lithic characters in 19 measured sections are graphically summarized. Standard reference to them is thus furnished.

The Riley formation comprises the basal Paleozoic strata of the Llano uplift. Its initial sediments were deposited on a submerged pre-Cambrian terrane having a known topographic relief as great as 800 feet. Its thickness normally averages about 680 feet but ranges from probably less than 200 to about 800 feet. At most places it is subequally divisible between the Hickory sandstone member below and

the Cap Mountain limestone member above, with the thin but widespread, glauconitic Lion Mountain sandstone member capping and completing the sequence.

The Wilberns formation includes five named members between the Riley formation and rocks of the Lower Ordovician Ellenburger group. It normally averages about 580 feet thick and ranges from 540 to 610 feet thick, but in the southeastern corner of the Llano uplift truncation of the upper beds has reduced it to 360 feet. The thin but widespread, nonglauconitic Welge sandstone member introduces the sequence. Above it is the Morgan Creek limestone member, grading to the succeeding argillaceous beds of the Point Peak shale. At the top of the sequence are the San Saba limestone and Pedernales dolomite members. These two are essentially equivalent and gradational facies, with the Pedernales normally overlying the San Saba.

INTRODUCTION

Names of Upper Cambrian units in the Llano uplift have been published by Barnes (1944, p. 37) and by Howell *et al.* (1944), who referred to unpublished work by Bridge and Barnes. Some of these units were in part described, and the Riley formation was named in a paper by Cloud, Barnes, and Bridge (1945, p. 154). The purpose of the present paper is to describe all the units named or redefined and thus furnish standard reference for them. The history of the older names is given by Wilmarth (1938). The nomenclature now in use for units of the Upper Cambrian is, in descending order, as follows:

Name	Normal average thickness
Wilberns formation	580
Pedernales dolomite member / San Saba limestone member	280
Point Peak shale member	160
Morgan Creek limestone member	120
Welge sandstone member	18
Riley formation	680
Lion Mountain sandstone member	37
Cap Mountain limestone member	280
Hickory sandstone member	360

The Upper Cambrian section in the Llano uplift (Pl. 1) is characterized by great variations in lithic character in short distances and by lesser differences in thickness in different portions of the area. These variations, together with facies changes of faunas and variations in abundance of fossils, have made correlation difficult.

Three types of variation may be recognized: (1) variation in lithic character due to original deposition, (2) changes in lithic character due to subsequent alteration, and (3) variation in thickness due to truncation, nondeposition, or difference in rate of deposition in different areas.

Examples of the first type are (a) intergradation between sandstone and limestone, typified in the Riley formation by lateral gradation of the upper part of the Hickory sandstone member into the basal part of the Cap Mountain limestone member and in the Wilberns formation by the gradation of the Welge sandstone member into the basal limestones of the Morgan Creek limestone member; (b) gradation from limestone to shale, exemplified in the Wilberns formation by the gradation of the Morgan Creek and San Saba limestone members into the Point Peak shale member; and (c) lateral gradations between sublithographic to microgranular, stromatolitic limestone and relatively coarse-grained, inequigranular limestone, shown in the San Saba beds

An example of the second type of variation is shown in the Wilberns formation by lateral gradation of dolomite (Pedernales dolomite member) into limestone (San Saba limestone member), a gradation which locally carries dolomite below a zone marked by the brachiopod *Plectotrophia* and reduces the Point Peak shale member to a thickness of but a few feet. This is not believed to be a condition of initial deposition but is rather due to replacement, which may have begun shortly after deposition and probably was accomplished during diagenesis. Naturally, dolomitic replacement of beds having the stratigraphic position of the Point Peak shale presupposes that such beds were originally limestones, probably because of local development of stromatolitic bioherms.

Examples of the third type of variation are indicated by the range in thickness of the Wilberns formation, exemplified by its thinning from the Threadgill Creek section in Gillespie County to the section along and near Pedernales River in Blanco County.

Plate 1 summarizes the stratigraphy of the Upper Cambrian of central Texas from information built up over a period of about 16 years. The work was started by C. L. Dake and Bridge and continued by Bridge. Subsequently Barnes, and still later Cloud joined the project. Responsibility for the various sections is as follows: Calf Creek—Cloud, Bridge, and Barnes; Bluff Creek—Cloud; Mason—Cloud and Barnes; Highway 87—Cloud; Camp San Saba—Bridge; Brady water well—examined by both Barnes and Cloud; Threadgill Creek, Squaw Creek, Pontotoc, and Slick Mountain—Barnes; Harris ranch—Cloud; Salt Branch—Cloud and Barnes; Little Llano River, Carter ranch, Everett ranch, and Point Peak—Bridge; Tanyard above *Plectotrophia*—Barnes; below *Plectotrophia*—Barnes and Cloud; Morgan Creek—Bridge; Backbone Mountain—Barnes; Hoover Point—Barnes and Cloud; Packsaddle Mountain—Barnes; Moore Hollow and East Canyon—Cloud; Cut Off Gap, White Creek, Pedernales River, and Scott Klett ranch—Barnes. The sections named make up the 19 sections on Plate 1, some of them being composite.

Bridge measured his sections before the Welge sandstone member of the Wilberns formation was recognized, and Barnes, in April 1946, checked these sections, placing the boundaries of the Welge and relocating the *Eoorthis* bed as a reference point. The correlation chart was assembled by Barnes and checked by Cloud. Bridges' absence from the country prevented him from finally checking his sections before publication. The profiles (Pl. 2) are by Bridge.

ACKNOWLEDGMENTS

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RILEY FORMATION

GENERAL STATEMENT

The Riley formation, a new name introduced by Cloud, Barnes, and Bridge (1945, p. 154), is defined as follows:

"The name Riley formation is . . . proposed to include all of the Cambrian strata in central Texas beneath the Wilberns formation. It includes, from base to top, rocks formerly known as the Hickory sandstone, the Cap Mountain formation, and the Lion Mountain sandstone member of the Cap Mountain formation. The contacts of these three rock units intergrade laterally, crossing faunal zones. For this reason they are here considered to be members of a single formation and are designated the Hickory sandstone, the Cap Mountain limestone, and the Lion Mountain sandstone members of the Riley formation

"The Riley formation takes its name from the Riley Mountains in southeastern Llano County, where the included members are well and typically exposed. Better sections of the Riley formation are known from other parts of the Llano region; but the only complete section in the Riley Mountains for which measurements are available is in the Moore Hollow area, about 18 miles by speedometer south of the town of Llano and west of the Llano-Click road. In this area Cloud computed thicknesses of 335 feet for the Hickory sandstone member, 421 feet for the Cap Mountain limestone member, and 24 feet for the Lion Mountain sandstone member; making a total of 780 feet for the Riley formation."

The name Riley formation might be confused with an earlier usage, "Riley series," involving some of the same rocks; and for this reason the following history of the name is given. The term Riley series, a name used by Comstock and Dumble (*in* Comstock, 1890) for some parts of the rocks here assigned to the Riley formation, has been rejected for use in the classification of the United States Geological Survey. Wilmarth (1938) summarizes this usage as follows:

"T. B. Comstock and E. T. Dumble, 1890 (Tex. Geol. Surv. 1st Ann. Rept., pl. 3, pp. lxi, 286–289). *Riley Series.*—In general sss., light red, shiny black, brown, yellow, and white. Includes some compact light-colored ls. Thickness probably 300 to 400 ft. Uncon. overlies Hickory series and uncon. underlies Katemcy or 'Potsdam' series. Includes Hickory ss. and part of Cap Mtn. fm. of present nomenclature. Named for Riley Mtns, Llano Co."

The thickness of the Riley formation in measured sections ranges from about 600 to almost 800 feet, due primarily to topographic irregularity of the overlapped pre-Cambrian terrane. In southwestern San Saba County, about 2.5 miles north-northeast of Pontotoc and in an area where the combined thickness of the Cap Mountain limestone and Lion Mountain sandstone members is only a little over 200 feet, the Cap Mountain limestone rests directly on pre-Cambrian rocks (Pl. 3, fig. 2), and the thickness of the Riley formation is thus probably less than 200 feet. It is thickest in southeastern Llano County and thinnest in the northwestern corner of the Llano uplift.

HICKORY SANDSTONE MEMBER

According to Wilmarth (1938) the name Hickory was first used as a series name by Comstock and Dumble in 1890, and was "Named for Hickory Creek, Llano Co." Paige (1912) called it the Hickory sandstone, and it was finally revised to member status by Cloud, Barnes, and Bridge (1945) as noted above.

The Hickory sandstone member of the Riley formation in general has not been carefully studied. It may be divisible into two parts. Ventifacts (Pl. 3, fig. 3) are present at the base of the Hickory sandstone at many localities in the Llano uplift (Barnes and Parkinson, 1940), and, with more detailed examination, it might be possible to map separately portions of aqueous and aeolian deposition. However, it is not known whether the aeolian elements are residual or reworked by aqueous agencies. In thickness the Hickory sandstone member averages about 360 feet and ranges from about 415 feet to a feather edge, variations being attributable to topography of the invaded area, irregularities in deposition, and lateral gradation to limestone of the

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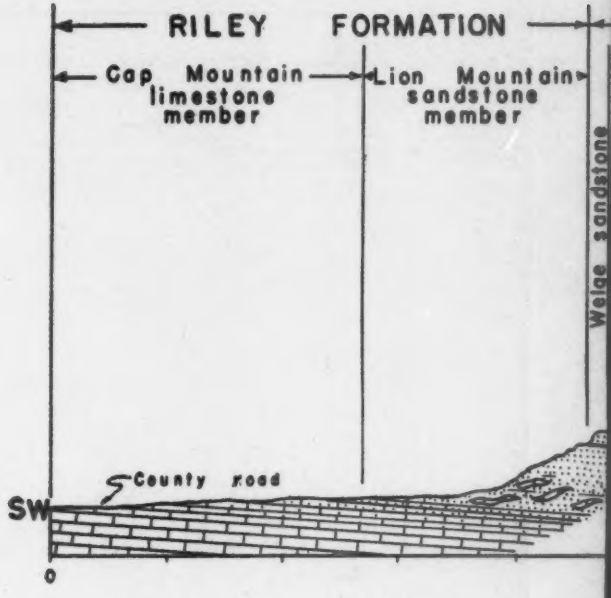
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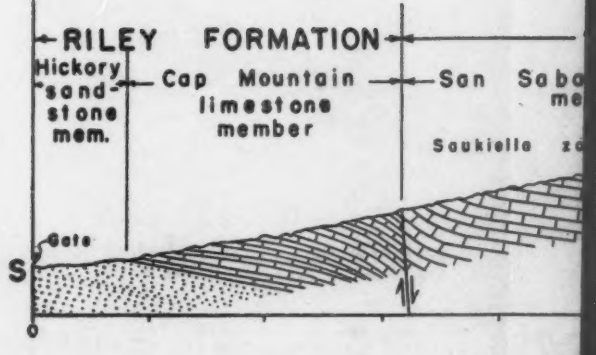
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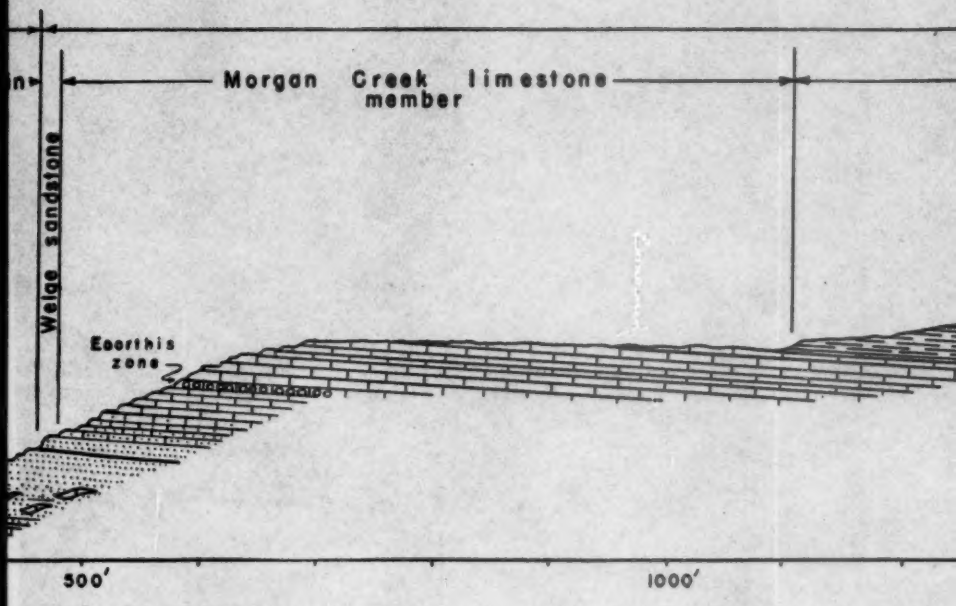

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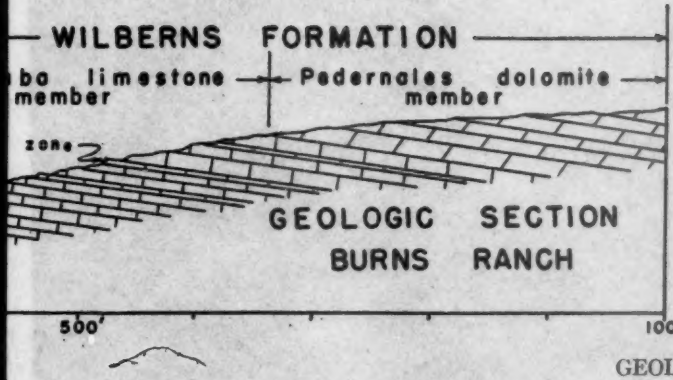

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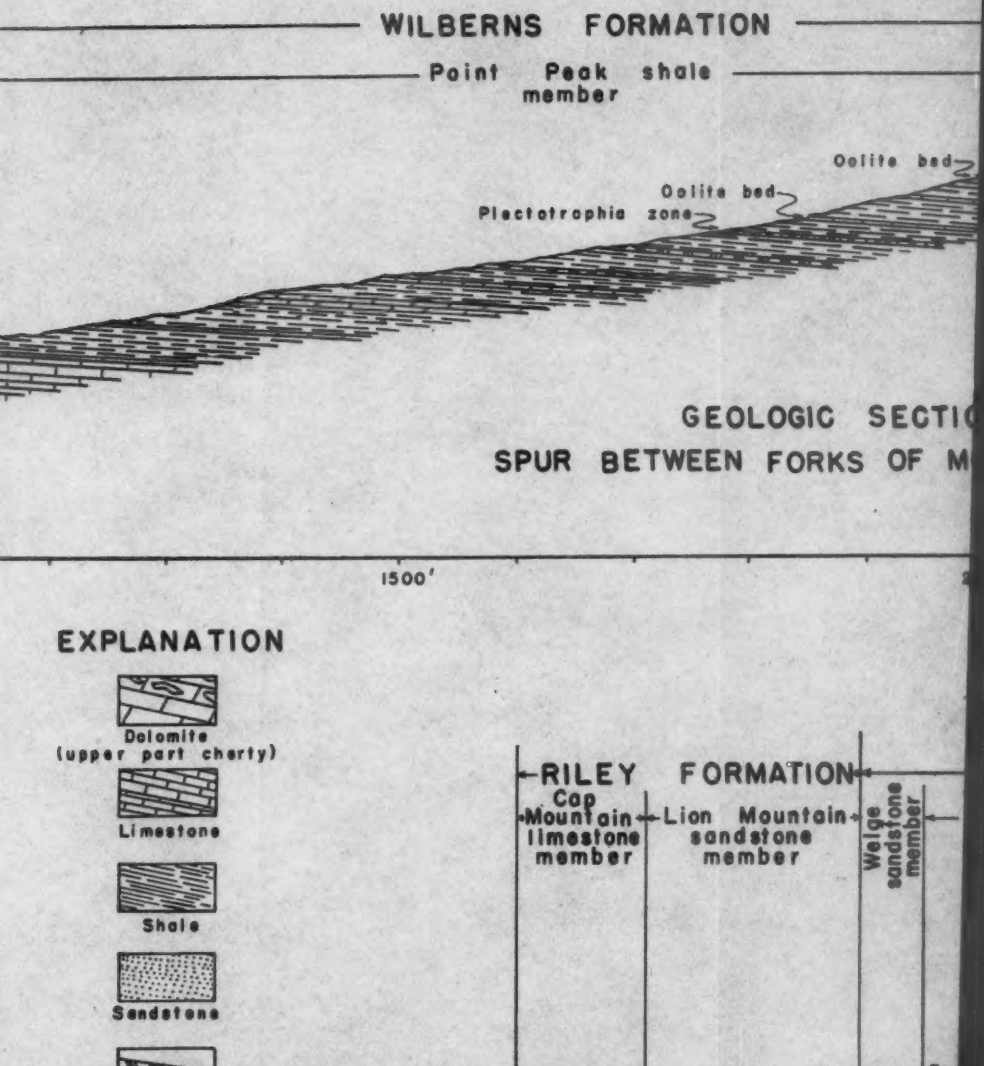
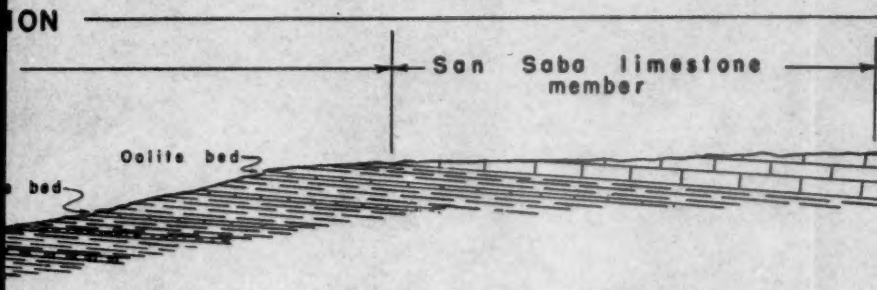


SECTIONS OF UPPER CAMBRIAN ROCKS, LLANO AND BURNET COUNTIES, TEXAS



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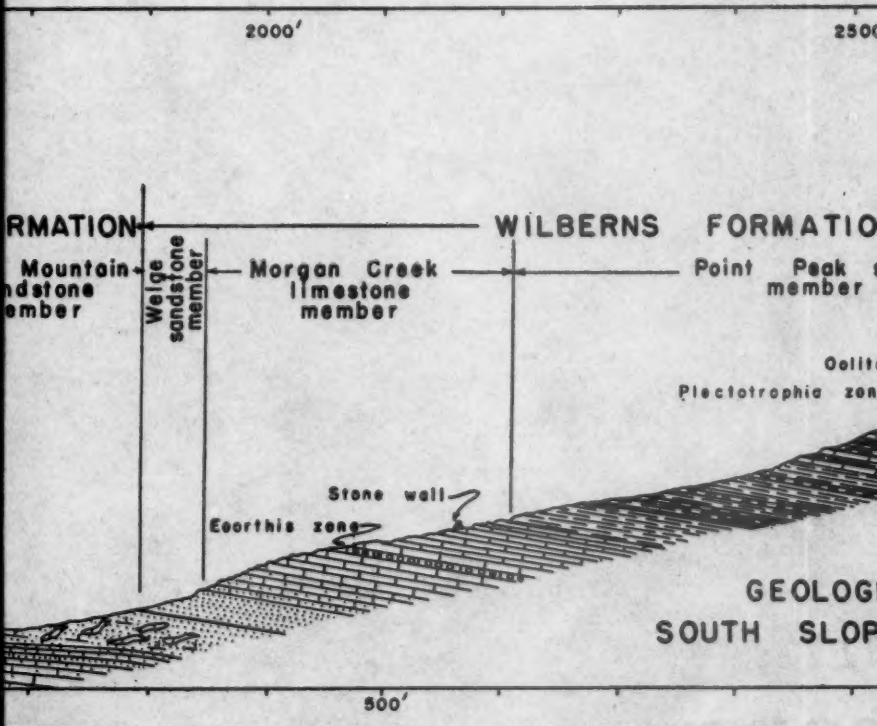

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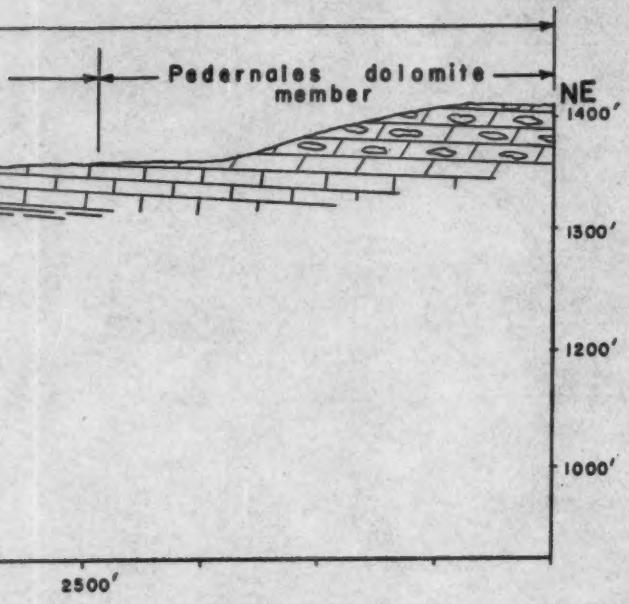

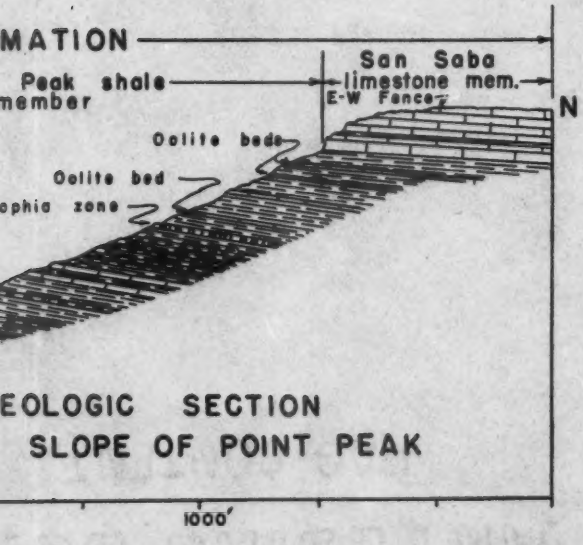

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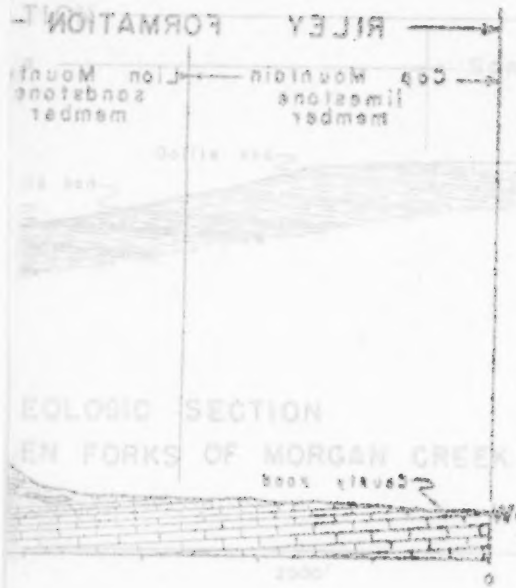
RILEY FORMATION
Cap Mountain limestone member

RILEY FORMATION
Cap Mountain limestone member

upper beds. The sandstones of the Hickory are noncalcareous; nonglauconitic; and yellow, brown, and red. In the western part of the Llano uplift the upper part is typically dull red or russet. Individual sand grains are angular to subrounded.

The Hickory sandstone member rests on an irregular pre-Cambrian surface having a relief as great as 800 feet at some places. Figure 1 of Plate 3 shows a small granite knob overlapped by Hickory sandstone, and Figure 2 of Plate 3 shows part of a hill of pre-Cambrian Valley Spring gneiss extending high into the Cap Mountain limestone member.

The Hickory sandstone as originally defined by Paige (1911) contains more beds than are allotted to the Hickory sandstone member of the present paper. The redefinition of the upper boundary of the Hickory sandstone member is given in the discussion of the Cap Mountain limestone member.

CAP MOUNTAIN LIMESTONE MEMBER

The Cap Mountain limestone member of the Riley formation as here defined is somewhat different from the original Cap Mountain formation of Paige (1911). The recognition of the Lion Mountain sandstone member of the Riley formation restricts it at the top, but more than counterbalancing this loss is the addition of beds at the bottom. The boundary is now placed at a distinct topographic (Pl. 3, fig. 4) as well as vegetational break which shows well on aerial photographs. This boundary is at the top of a noncalcareous sandstone zone and beneath a zone of alternating impure, dark-brown limestones and calcareous sandstones which become more calcareous upward; finally grading into the fairly pure, granular limestones that comprise the bulk of the member. The amount of calcareous material in the gradational lower part of the member varies greatly from place to place. For example, the lower beds are highly calcareous on Lion Mountain, but they are quite sandy at the type locality on Cap Mountain and on Packsaddle Mountain. Formerly the Hickory-Cap Mountain boundary was placed at an indefinite point within the sequence of calcareous sandstones in the lower part of the Cap Mountain limestone member of the present report.

The Cap Mountain limestone member, especially in the eastern part of the Llano uplift, is typically a massive, cliff-forming member (Pl. 4, figs. 1–3; Pl. 5, fig. 2). It ranges from about 135 to 455 feet thick, with an average thickness near 280 feet, and with variation due principally to lateral gradation to sandstone of the lower beds.

LION MOUNTAIN SANDSTONE MEMBER

The Lion Mountain sandstone member of the Riley formation was named by Bridge (1937) as the top member of the Cap Mountain "formation;" it is named from Lion Mountain in the northwestern part of the Burnet quadrangle. It now becomes the top member of the Riley formation, since Cap Mountain as a formation name has been dropped. Otherwise it retains the definition originally given by Bridge. The name applies to a zone of highly glauconitic sandstone, containing in the lower part tangential lenses of limestone (Pl. 4, fig. 4) that are essentially composed of trilobites, as well as some rather continuous highly glauconitic limestone

beds containing phosphatic brachiopods. The upper boundary is sharp, but the lower boundary grades into limestone. In mapping, the lower boundary is most conveniently located at the lower edge of a sparsely vegetated bench.

The Lion Mountain sandstone is only about 20 feet thick in the type section. It attains a maximum measured thickness of 50 feet and extends throughout the Llano uplift. It is excellently exposed on Squaw Creek in Mason County about half a mile from the Gillespie County line (Pl. 4, fig. 5).

WILBERNS FORMATION

GENERAL STATEMENT

The Wilberns formation was named by Paige (1911), for Wilberns Glen in Llano County.

Present usage retains the lower boundary of the Wilberns formation as defined by Paige (1911; 1912), but the upper boundary was redefined and placed at the top of the Cambrian by Cloud, Barnes, and Bridge (1945). The Wilberns formation is divided into five members, the names being used with scant definition by Barnes (1944) and by Howell *et al.* (1944). Through most of the Llano uplift the Wilberns formation ranges from 540 to 610 feet thick; but in the southeastern corner of the region (Scott Klett ranch and Pedernales River sections) it is only about 360 feet thick, because of truncation and disconformity at the top. Its average thickness is about 550 feet if the thin section of the southeastern corner is considered, and about 580 feet if that section is discounted.

WELGE SANDSTONE MEMBER

The Welge sandstone member of the Wilberns formation is named by Barnes from the Welge land surveys between Threadgill and Squaw creeks, Gillespie County, where it crops out. The best exposure of the Welge sandstone in this area, here designated the type section, is along Squaw Creek half a mile north of the Gillespie County line. The photograph of an outcrop of the Welge sandstone on Squaw Creek (Pl. 4, fig. 5) is upstream from the best exposure, which is in a poor position to photograph. The Welge is a brown, mostly nonglauconitic sandstone which grades upward into the Morgan Creek limestone member. Much of the Welge sandstone has quartz grains with recomposed faces which glitter in the sunlight. The contact with the Lion Mountain sandstone member of the Riley formation beneath is abrupt.

At the type locality in Gillespie County the Welge sandstone member is 27 feet thick. It extends throughout the Llano uplift, averaging 18 and ranging from 9 to 35 feet thick. The thicker sections are along the northern and western sides of the uplift.

MORGAN CREEK LIMESTONE MEMBER

The Morgan Creek limestone member of the Wilberns formation is named by Bridge from exposures on both the north and south forks of Morgan Creek in Burnet County. In the type section, exposed on the point just north of the junction of the two forks, it is about 110 feet thick. The Morgan Creek limestone ranges from

FIGURE 1. HICKORY SANDSTONE MEMBER OVERLAPPING PRE-CAMBRIAN GRANITE
South end of Backbone Ridge, Burnet Co.

FIGURE 2. CAP MOUNTAIN LIMESTONE MEMBER OVERLAPPING PRE-CAMBRIAN VALLEY SPRING GNEISS
Southwestern San Saba Co., 2.5 miles north-northeast of Pontotoc. Overlap marked by hammer (top end of stick); Cap Mountain beds dip into background and thin-bedded gneiss dips steeply to right.

FIGURE 3. VENTIFACTS FROM BASE OF HICKORY SANDSTONE
Southwestern Llano Co., along Cherry Spring-Llano road, .5 mile north of Gillespie Co. line.

FIGURE 4. EASTERN PART OF PACKSADDLE MOUNTAIN, LLANO CO.
Showing bench at Hickory-Cap Mountain contact. Base of Hickory sandstone (€rh) marked by large blocks of sandstone in line with tops of mesquite trees in foreground. Downdropped block of Cap Mountain limestone (€rc) on left capped by Lion Mountain sandstone member (€rl) of Riley formation. Foreground occupied by pre-Cambrian Packsaddle schist (ps).

HICKORY SANDSTONE AND CAP MOUNTAIN LIMESTONE MEMBERS OF THE RILEY FORMATION

FIGURE 1. PACKSADDLE MOUNTAIN, LLANO CO.
South end, west of saddle, showing cliff of Cap Mountain limestone member.

FIGURE 2. CLOSE VIEW OF FAR POINT OF FIGURE 1
Showing heavy bedding of Cap Mountain. Hickory sandstone member and pre-Cambrian schists intervene between cliff and dropped Riley Mountains in distance.

FIGURE 3. CLOSE VIEW OF PART OF SAME CLIFF OF CAP MOUNTAIN LIMESTONE
Showing many individual strata in bluff.

FIGURE 4. LION MOUNTAIN SANDSTONE MEMBER OF RILEY FORMATION
Along south fork of Morgan Creek, Burnet Co. White cross-beds are trilobite-coquinas in calcareous, glauconitic sandstone.

FIGURE 5. UPPER RILEY AND LOWER WILBERNS STRATA
On Squaw Creek, Mason Co., .5 mile north of Gillespie Co. line. Lower left to upper right—Lion Mountain sandstone member between creek and first massive bed; travertine-coated Welge sandstone member of Wilberns formation forms bluff and grades upward to well-bedded Morgan Creek limestone.

about 70 feet thick in the Point Peak and Carter ranch sections to about 160 feet thick in the Salt Branch section and averages about 120 feet. The member consists of medium- to coarse-grained, abundantly glauconitic, well-bedded limestone (Pl. 5, figs. 2, 3; Pl. 6, fig. 1). The lower beds at the contact with the Welge sandstone member are somewhat sandy. The lower portion of the member is commonly reddish, the red tones becoming less pronounced and finally grading upward into gray or greenish-gray limestone. In many sections there is a shaly zone in the upper part of the Morgan Creek limestone member; and, in areas where the limestone above this shale is thin, the boundary is arbitrarily chosen. The individual layers of limestone are from 4 inches to a foot or more thick, and the thickness of any one bed is rather uniform. The lithic character of the member is, in general, quite uniform. The Morgan Creek member carries the well-known *Elvinia* fauna in the lower part, with the conaspid fauna coming in above. The conaspid fauna is divided into the *Eoorthis* and *Billingsella* subfaunas, but *Billingsella* actually overlaps the brief range of *Eoorthis* locally to occur with *Elvinia*. The *Billingsella* subfauna, therefore, is marked by the presence of *Billingsella* in the absence of, and succeeding, *Eoorthis* and *Elvinia*. At a few places *Elvinia* has been seen with *Eoorthis*, but it has not been recorded above *Eoorthis*.

In a section measured on the Scott Klett ranch near Pedernales River in Blanco County, the Morgan Creek limestone member is 140 feet thick. In the portion of the section beneath the *Billingsella* subzone, in addition to the beds having the normal lithology of those in the type section, there are three beds of oölitic limestone, one 10-inch bed of stromatolites interspersed with intraformational conglomerate, one layer of mudballs, and 3 feet of shale. One of the three beds of oölitic limestone is 7.5 feet thick. Numerous thin stromatolitic bioherms occur in the upper part of the Morgan Creek limestone in this area. One thin-bedded, shaly limestone zone, 7.5 feet thick, is also present.

POINT PEAK SHALE MEMBER

The Point Peak shale member of the Wilberns formation is named by Bridge from Point Peak (Pl. 2; Pl. 5, fig. 1), a conspicuous, isolated hill about 4 miles northeast of Lone Grove, Llano County. In the type section, on the south slope of Point Peak it is about 270 feet thick. In this section it is overlain by about 20 feet of the girvanella beds of the San Saba limestone member and is underlain by a full but thin section of the Morgan Creek limestone member. The Point Peak shale is thickest in the Point Peak section and thinnest in the Scott Klett ranch section, along Pedernales River in Blanco County, where it is but 25 feet thick. Excluding these two sections it averages about 160 feet thick and thickens from the southeastern part of the uplift to the northeastern part. Variation in thickness is attributable principally to facies changes, and, to a lesser extent, to irregularity in sedimentation. The Point Peak shale does not appear to have been recognized in deep wells except immediately north of the Llano uplift.

The Point Peak shale member consists of well-bedded, soft, greenish, calcareous shales with subordinate amounts of fine-grained, compact dolomite; medium- to fine-grained glauconitic limestone; intraformational conglomerates; and, near the

top, occasional beds of oölitic limestone and commonly extensive (Pl. 8, fig. 2) to scattered (Pl. 7; Pl. 8, fig. 1) stromatolitic bioherms that locally coalesce to form biostromes. The dolomites occur in large lenticular masses arranged in one or more layers, most abundant in the lower portion of the unit. Seen from above, the masses are circular to elliptical in outline, 1 to 4 feet or more in diameter. They show no fine structure but are thought to be algal in origin. The limestones are similar to those of the underlying Morgan Creek but are commonly finer-grained. The intraformational conglomerates consist of layers of compact limestone up to 18 inches thick, crowded with angular, flattened limestone pebbles of various sizes and colors. The beds of this material are discontinuous and cannot be matched in closely adjacent sections. They occur chiefly in the Point Peak shale member, and locally in the San Saba limestone.

Fossils are locally common in the Point Peak shale member. Thin limestones near the base of the unit commonly carry *Billingsella*, and species of that genus occur intermittently through the member. In the northeastern part of the uplift a 12- to 30-inch bed of medium-grained, glauconitic limestone about 30 to 60 feet below the top of the member contains silicified shells of *Plectotrophia bridgei* Ulrich and Cooper and a large alate species of *Billingsella*. These fossils are extremely abundant at some places, characterizing the *Plectotrophia* zone. This zone has been found in all parts of the uplift except in the section on Pedernales River, and it is an important, easily recognized marker. Except in the extreme eastern part of the uplift it appears to retain fairly constant lithic and faunal characters and to hold a fairly constant stratigraphic position. It is thus, at most places, an important datum from which lithic fluctuations may be measured. However, in Burnet County, south of Sudduth, *Plectotrophia* has a stratigraphic range of at least 40 feet.

Decker (1945, p. 13–61) described graptolites from the Point Peak shale member, obtained 70 feet beneath a zone characterized by the huenellid brachiopod *Mesonomia* which appears to supplant the huenellid *Plectotrophia* in an area southwest of Mason. At this point *Mesonomia* is 10 feet beneath a thick zone of stromatolites.

The top of the Point Peak shale member drops abruptly southward in the Sudduth area of Burnet County. At a point 1.5 miles south of Sudduth the top of the Point Peak shale (which here is in contact with Pedernales dolomite) is about 80 feet beneath the alate *Billingsella* bed. North of Sudduth, 1.5 miles, this bed is in shale just beneath the Pedernales dolomite. Within 3 miles in a north to south direction the top of the Point Peak shale thus drops about 80 feet. Along Pedernales River in Blanco County the top of the Point Peak shale has dropped still more. *Plectotrophia* was not found in the measured section along Pedernales River, but a specimen of *Plectotrophia* found at a locality near by was associated with chert similar to that seen 37 feet beneath the Ordovician contact in the measured section. If this is the horizon of *Plectotrophia* it is about 150 feet above the top of the thin-bedded interval considered to be Point Peak shale.

The bottom boundary of the Point Peak shale likewise is not at a constant stratigraphic horizon. It ranges from 90 feet above the base of the Wilberns formation on Point Peak to about 170 feet in the Salt Branch section. The difference in position of the boundary above the base of the Wilberns seems to be due chiefly to facies change from shale to limestone.

SAN SABA LIMESTONE MEMBER

The San Saba limestone member of the Wilberns formation is named by Bridge from exposures along and near San Saba River, northwest of Camp San Saba, McCulloch County. The type section, about 280 feet thick, is exposed along both sides of the Mason-Brady highway, beginning at the bridge across the San Saba River and extending northward for 0.7 mile, at which place it is in collapse contact with the limestones of the Threadgill member of the Tanyard formation.

The name San Saba was originally used as a series term by Comstock (1890) who applied it either to these beds or to some part of them. Dake and Bridge (1932) called these beds "Post Wilberns," correlated them with the Fort Sill and Signal Mountain formations of the Arbuckle and Wichita mountains, and suggested that Comstock's name San Saba might well be revived for a part of them. The name is now applied to the entire series of more or less glauconitic limestone overlying the Point Peak shale member of the Wilberns formation and underlying the Threadgill member of the Tanyard formation (Pl. 6, figs. 2–4; Pl. 8, fig. 3). The San Saba limestone member is replaced eastward by the Pedernales dolomite member. It grades downward into the Point Peak shale member, its lower boundary being drawn on lithic grounds and not at a definite stratigraphic horizon.

The Point Peak—San Saba boundary, chosen during the early phases of the Ellenburger mapping (Cloud, Barnes, and Bridge, 1945) in areas where stromatolitic bioherms do not occur near the boundary, was the top of the highest significant shale. For such areas this seems to be better field practice than choosing an intermediate boundary in the gradation from limestone to shale. Where bioherms occur at this boundary, however, its selection commonly depends on lateral tracing and the consensus of varied factors. At Camp San Saba a zone of stromatolitic bioherms of bluish-green sublithographic to microgranular limestone (the "Stromatocerium pavement" of Comstock, 1890) occurs between well-bedded, inequigranular limestones of the San Saba member and shales of the Point Peak member. The bioherms are not continous but are a series of separate masses in a zone as much as 80 feet thick that at places appears to be represented by shale and at other places by bedded limestone. In the type section of the San Saba limestone member the zone of stromatolitic bioherms is now included with the Point Peak shale member, although it was originally considered to belong to the San Saba limestone member. Additional evidence for the placing of this thick zone of bioherms with the Point Peak shale is the presence of shale above the biohermal zone and below well-bedded, granular limestones of the San Saba member west of the Mason-Brady highway. In Gillespie County large stromatolitic bioherms are located both above and below this position; and the upper one, well exposed on Squaw Creek, is definitely within the San Saba limestone member. Where these stromatolitic bioherms are between limestone above and shale below, the member with which they should be mapped must be separately determined in each individual area. Considering regional factors and the relationship of the bioherms to the *Plectotrophia* zone, however, most of the bioherms at this position probably belong at the top of the Point Peak shale member. Most of these zones of stromatolitic bioherms are large enough to be mapped separately and should be so mapped to obtain more information about their vertical and lateral distribution.

The top boundary of the San Saba limestone member is the Cambrian-Ordovician contact in the western part of the Llano uplift and the contact with the Pedernales dolomite member elsewhere. In the type section the contact is obscured by collapse, but on Threadgill Creek (Pl. 8, fig. 3), although in full view, it is yet very difficult to place. Sedimentation seems to have been continuous across the systemic boundary in the western part of the Llano uplift, contrasting with the disconformable Cambrian-Ordovician boundary in the eastern part of the uplift where it is in dolomite (Pl. 8, fig. 4). In mapping practice in the western areas, the boundary is chosen by finding the highest glauconite and the approximate faunal boundary and striking a mean. Each of the two types of evidence usually places the boundary within a few feet.

Cloud, during April 1945, in connection with a description of the overlying rocks of the Ellenburger group, described the upper 30 feet of the stromatolitic zone at the top of the Point Peak shale member and the full thickness of 200 feet of San Saba beds in a section north along U. S. highway 87 from the bridge over San Saba River.

Approximately the upper 80 feet of the Point Peak shale member in this section is represented by a zone of stromatolitic bioherms. Only the upper 30 feet of this zone was studied closely, and it is limestone with occasional zones of dolomite to the top of the biohermal zone. The limestone is microgranular to sublithographic, in part a fine pellet limestone; greenish to brownish gray to woodash gray or light yellow, in part with yellowish argillaceous films. It weathers medium bluish gray to woodash gray. The dolomite is very fine-grained to microgranular, brownish to yellowish gray. It weathers medium gray to brownish gray. The beds are generally fairly thick; those measured are from less than 1 inch to 14 inches thick, but some beds are probably much thicker than this. The stromatolitic portions of this interval weather to large, subcircular, hummocky, reticulated masses. *Stenopilus* was collected near the base of the interval in December 1940 during a field trip led by Bridge and Barnes. About 40 feet of concealed beds intervenes between the 30 feet described and a 10-foot biohermal interval in the bed of San Saba River under the bridge.

Above the stromatolitic limestones at the top of the Point Peak shale member in the section north from San Saba River about 200 feet of mostly granular limestone is assigned to the San Saba limestone member, constituting its type section.

The next 60 feet of beds above the stomatolitic zone is limestones which are conspicuously granular in appearance; they vary from very fine- to coarse-grained, in general crowded with fine to fairly coarse pelletlike bodies and with several beds crowded with fragments of trilobites and other fossils, especially in the lower few feet. Rare interbeds of limestone in this interval are similar to that described in the following paragraph (top interval of the San Saba). The color is grayish brown to brownish gray to yellowish brown and yellowish gray, in part with scattered to abundant chrome-green specks of glauconite, and with local beds that are quite green. Beds 1 to 16 inches thick, are mostly less than 8 inches thick. They weather gray to brownish gray, in part with yellowish tinges. Glauconite was the only mineral noted that would be insoluble in hydrochloric acid, but acetic insolubles of many beds probably would yield abundant dolomite grains. The glauconite is generally

FIGURE 1. PROFILE OF POINT PEAK, LLANO CO.
Viewed from west, showing scarp slope to right and dip slope to left. San Saba limestone member of Wilberns formation caps dip slope, and type section of Point Peak shale member is in scarp between it and Morgan Creek limestone member. Top of Morgan Creek beds form bench midway up scarp slope.

FIGURE 2. "PICTOGRAPH CAVE" ON ONION CREEK, GILLESPIE CO.
Rock at right of fault is Cap Mountain limestone member of Riley formation, and that at left is Morgan Creek limestone member of Wilberns formation.

FIGURE 3. MORGAN CREEK LIMESTONE MEMBER
On north bank of San Saba River at Flatrock Crossing, .5 mile east of highway bridge at Camp San Saba, McCulloch Co. For fossil zones *see* Bridge and Girty (1937, Pl. 66, fig. B).

STRATA OF THE UPPER RILEY AND LOWER WILBERNS FORMATIONS

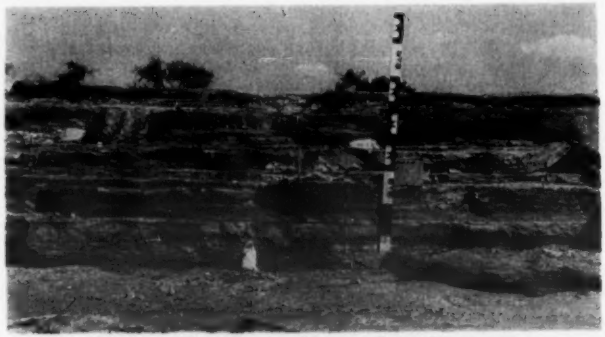

FIGURE 1. NEAR VIEW OF MORGAN CREEK LIMESTONE
Same locality as shown in Figure 3 of Plate 5. Hammer on *Eoorthis* bed.

FIGURE 2. GIRVANELLA BEDS OF SAN SABA LIMESTONE
In normal contact (head of hammer) with Point Peak shale along Everett ranch road 1.5 miles north of Point Peak, Llano Co.

FIGURE 3. GIRVANELLA BEDS OF SAN SABA LIMESTONE
In glen west of Everett ranch road, Llano Co., about 200 yards north of locality of Figure 2.

FIGURE 4. THICKLY BEDDED SANDSTONE IN SAN SABA LIMESTONE MEMBER (RIGHT)
Faulted against Point Peak shale (left). West bank of Leon Creek, a mile southeast of crossroads at Erna, western edge of Mason Co.

not abundant, but it is common enough to be found without difficulty, and some thin beds are quite crowded with glauconite globules. Saukiinid trilobites, determined by Bridge as *Saukiella* sp., were collected in a little outlying pocket of basal beds of this interval in December 1940 during a field trip led by Bridge and Barnes. The lower few feet of the interval is highly fossiliferous, being crowded with trilobites.

The top 140 feet of beds is predominantly limestone, with some yellow- to buff-weathering dolomitic patches. Except for the upper and lower few feet, which contain sublithographic, medium-bluish-gray and yellowish-gray to brownish-gray patches, the limestone in this interval is conspicuously granular. It varies from microgranular to coarse-grained and in general is crowded with fine to coarse pellet-like bodies. It is mostly brownish to greenish gray to grayish brown, with local patches and specks of yellow buff or cinnamon where dolomitic and locally with scattered to abundant yew- to chrome-green specks of globular glauconite. Beds are from a fraction of an inch to 6 inches thick and weather brownish gray to greenish and bluish gray to grayish brown. In part there are yellow to buff tinges, mottles, and blotches and locally very light-bluish-gray to woodash-gray mottles and patches. The upper and lower few feet especially are marked by thin beds that weather mottled in yellow to buff and light bluish gray to woodash gray. The ledges that result from weathering are thin, in part solution-pitted, and in general not well exposed. Globular glauconite occurs occasionally throughout the interval; it is quite abundant in some beds. Several of the beds are crowded with fragments of trilobites and gastropods, with *Kingstonia*-like trilobites occurring in medium- to coarse-grained granular limestone near the top of the interval; but no fossils were collected. The attitudes and sequence of the beds in the upper part of the interval are obscured by collapse, and in general the Cambrian-Ordovician contact in the vicinity of the highway is not well marked.

Bridge noted fragmentary specimens of the trilobite *Briscoia* about 95 feet below the top of the San Saba limestone member of the Wilberns formation in the type section and a small planispiral gastropod near the top. The *Saukiella* bed mentioned by Cloud at the base of the middle interval is described by Bridge as a 12- to 18-inch bed of yellow, medium-grained, glauconitic, extremely fossiliferous limestone. This bed was noted by Dake and Bridge (1932) as far east as the valley of East Deep Creek north of Pontotoc. They were unable to recognize this unit farther east and ascribed this fact to an erosion period within the late Cambrian followed by a reinvasion from the northeast in yet later Cambrian time. It now appears that the trilobite beds are replaced laterally by limestones containing marble-sized subspherical stromatolites known as "girvanella," and that the enviroment represented by these was not generally suitable for trilobites. The *Saukiella* zone is not well developed in areas where girvanellas are abundant. Later, Bridge found a few saukiinid trilobites in the girvanella beds on the Llano-San Saba highway (Texas 16) and elsewhere in the northeastern part of the uplift. A fair representation of the *Saukiella* fauna was also found by Bridge on Burns' ranch (Pl. 2) about 5 miles northwest of New Bluffton, in Llano County. At this locality about 50 feet of girvanella-bearing beds are exposed above a fault. These are overlain by an equal thickness of

compact, fine-grained limestones without girvanellas, and this is followed by about 100 feet of the Pedernales dolomite member of the Wilberns. The *Saukiella* bed occurs in limestones just above the girvanella beds.

In Gillespie County and adjoining areas the *Saukiella* zone is well developed and has been found by Barnes at numerous localities and in sections where its relation to overlying and underlying faunas can be definitely established.

The San Saba limestone member is the most variable unit of the Wilberns sequence and shows marked facies changes from place to place. In the vicinity of Point Peak (Pl. 6, figs. 2, 3), and extending throughout most of the northeastern portion of the Llano uplift, the San Saba limestone differs from that exposed in the type section. It is massive and contains many girvanellas. In the Camp San Saba section about 5 feet of girvanella limestone is present, whereas in the Point Peak area the maximum thickness is about 150 feet. At places, notably in a section north of the mouth of Fall Creek, girvanella beds constitute the entire San Saba limestone member. The girvanellas are light gray to almost white and are surrounded by a deeper-gray matrix which is streaked and mottled by light yellows and browns. On steep slopes the girvanella limestone forms conspicuous bluffs and appears to be massively bedded, whereas on gentler slopes it breaks down to thin slabs. Earlier workers (Paige and others) drew the base of the Ellenburger at the base of such bluffs; but where the San Saba limestone member had broken down to gentle slopes the Wilberns-Ellenburger contact was drawn at some higher position, commonly the base of the first massive limestone or dolomite bed. In some sections there is a variable thickness of compact, thin-bedded limestone without girvanellas between the girvanella beds and the Pedernales dolomite member of the Wilberns; but at other places dolomitization has extended downward to include part or all of the girvanella beds. As much as 60 feet of dolomitized girvanella beds has been noted. Girvanella beds are not restricted to the San Saba limestone member and equivalent dolomites of the Pedernales, however. In some areas they are common in limestones of the Point Peak shale member of the Wilberns, and girvanellalike bodies have been seen by Barnes in the Cap Mountain limestone member of the Riley formation.

Along Threadgill Creek, in the southwestern part of the Llano uplift, the lithic character of the San Saba limestone member is similar to that in the type section, except that it is more persistently granular and considerably more fossiliferous. Stromatolitic bioherms are absent in the San Saba limestone along Threadgill Creek but are well displayed to the east along Squaw Creek. The transition of these beds eastward into the Pedernales dolomite member has already been noted.

In the vicinity of Calf Creek, in northwestern Mason County, a body of calcareous sandstone is present in the San Saba limestone member. Cloud measured a section on the north bank of San Saba River below Calf Creek. A résumé of his section going up from beds that have the lithic characters of the Pedernales dolomite member is as follows: calcitic and dolomitic sandstone, 47 feet; arenaceous limestone, 10 feet; calcitic and dolomitic sandstone, 16 feet; and glauconitic limestone and minor calcitic sandstone beds, 55 feet. The section ends at the base of the limestone of the overlying Threadgill member of the Tanyard formation (Ellenburger group). A composite sample, collected from fresh exposures of the upper 45 feet of sandy beds

along Calf Creek, was leached in hydrochloric acid, and from the amount of residue remaining it is estimated that this interval contains more limestone than sand. A screen analysis of the sand indicates that it is well sorted, with 47.0 per cent between 0.589 and 0.295 mm., and with 47.4 per cent between 0.295 and 0.147 mm. in size. Beneath the sequence of limestone and calcareous sandstone is dolomite like that of the finer-grained and darker parts of the Pedernales dolomite member. This is the only area examined in which the normal positions of the calcitic facies of the upper Wilberns formation (San Saba limestone member) and the dolomitic facies of the upper Wilberns (Pedernales dolomite member) are reversed.

Sandstone and calcareous sandstone are common in the San Saba limestone member along and near Llano River in western Mason County (Pl. 6, fig. 4). Plummer (1943) described quartz sand in the Cambrian of Mason county which he termed the Erna sand. Cloud, in mapping along Llano River southwest of Mason, found several calcareous sandstone intervals in the San Saba limestone member, four of which were noted in a section to be described in a final report of the work on the Ellenburger group by Barnes and Cloud. In résumé this section, going up from the top of a zone of large stromatolitic bioherms near the mouth of Bluff Creek, is as follows: limestone, 60 feet; arenaceous limestone, 7 feet; limestone, 8 feet; silty limestone with occasional pockets and beds of sand, 30 feet; limestone, 56 feet; calcareous sand and arenaceous limestone, 21.5 feet; limestone, 44.5 feet; calcareous sand and arenaceous limestone, 7 feet; and limestone, 28 feet, to the base of the Threadgill member of the Tanyard formation. These sandstones are absent in the Threadgill Creek and Camp San Saba sections, approximately 22 miles to the southeast and the same distance to the northeast respectively from the Bluff Creek section. In view of the varied number and local character of the sandy zones in the San Saba limestone member of western Mason County it seems undesirable that any of them be formally named.

The average thickness of the San Saba limestone and Pedernales dolomite members, taken as a unit, is about 280 feet.

PEDERNALES DOLOMITE MEMBER

The Pedernales dolomite member is a dolomite facies of the upper part of the Wilberns formation developed mostly in the eastern part of the Llano uplift. It commonly replaces and is equivalent to a variable part of the upper part of the San Saba limestone member, which is characteristic of the upper Wilberns in the western part of the uplift. Along Pedernales River, in western Blanco County, the Pedernales dolomite replaces the entire San Saba limestone member and includes beds equivalent to most of the Point Peak shale member as well. The Pedernales dolomite member was originally included in the "Ellenburger limestone" because of lithic similarities. It is that part of the former "Ellenburger limestone" which Dake and Bridge (1932) called the Potosi and Eminence faunal equivalents, and its removal from the revised Ellenburger group and inclusion in the Wilberns formation necessitate a redefinition of the Ordovician and Cambrian beds above and below the systemic boundary. This has been done by Cloud, Barnes, and Bridge (1945).

The Pedernales dolomite member is named by Barnes for Pedernales River, along

which it is well exposed in the type section from 1.5 to 3 miles upstream from the bridge on the Johnson City—Marble Falls highway a mile north of Johnson City, Blanco County. Although the base of the Pedernales extends lower in the section here than at other places in the Llano uplift, thicker sections of the member have been measured in the Tanyard and Backbone Mountain sections. This is probably due to pre-Ordovician truncation of the upper beds of the Pedernales dolomite member in the vicinity of the type section.

Cloud, Barnes, and Bridge (1945) describe the rocks in the type section as follows:

"The bottom 86 feet of the Pedernales dolomite member of the Wilberns is fine grained and evenly bedded, contrasting sharply with the overlying massive (coarse grained) portion. The coarse grained dolomites are predominantly light gray and silvery gray with occasional intervals that are yellowish gray or nutria. The fine grained dolomite is predominantly yellowish gray to beige with some nutria in the upper part. The entire dolomite section of the Johnson City area is speckled to mottled with dull, dark reddish purple in varying degrees. Glauconite, common elsewhere in the upper Wilberns, was not noted except in the basal few feet of beds of the Pedernales dolomite member in the Johnson City area.

"The type section of the Pedernales dolomite member of the Wilberns contains some chert, mostly near the top of the lower fine grained portion. It is mostly fine grained, minutely to coarsely quartzose, compact to very porous, and medium brown to various shades of dirty gray and white. The chert is irregularly porous. It does not display distinct molds of either dolomite rhombs or oölids. Four miles to the northeast of the type section, chert of similar appearance is much more abundant in the Pedernales."

On Backbone Ridge, in Burnet County, the Pedernales dolomite member is 224 feet thick and is fine-grained. At the Tanyard, in northern Burnet County, it is 277 feet thick and has upper and lower fine-grained zones and a middle coarse-grained zone. In the Cherokee area it is estimated to be 90 feet thick and is fine grained.

The basis for considering the Pedernales dolomite and the San Saba limestone members to be approximate contemporary facies is twofold: (1) complementary variations in thickness and stratigraphic position between definite faunal and lithic boundaries, and (2) direct paleontologic evidence. Dake and Bridge (1932) recognized two faunal horizons in what is now called the Pedernales dolomite member. The upper is a very late Upper Cambrian assemblage characterized by species of *Stenopilus*, *Eurekia*, *Euptychaspis*, *Plethometopus*, *Plethopeltis*, and certain undescribed gastropods. This fauna, originally found in chert boulders from Colorado River westward to the Llano-San Saba highway, was subsequently found by Barnes in an inch-thick limestone interbedded with massive dolomite along Rocky Creek in the valley of Pedernales River, Blanco County, and the same fauna occurs near the top of the San Saba limestone member in the Threadgill Creek section and elsewhere in Gillespie County, in the western part of the uplift.

The lower fauna, also of late Upper Cambrian age, is characterized by species of *Scaevogyra*, *Platycolpus*, and *Plethometopus*. This fauna was originally found by Dake and Bridge on Colorado River just above the mouth of Fall Creek, and they interpreted its failure to be present farther west, together with the thinning of the dolomite, as evidence of transgressive overlap. Subsequently this fauna has been found by Bridge in chert preservation in dolomite at a few other localities in the northeastern part of the uplift, notably at the top of the Morgan Creek section, and by Barnes in massive stromatolitic limestone near the top of the Wilberns formation in Gillespie County, in the western part of the Llano region. Although the ex-

South side of Llano River downstream from White's Crossing, Mason Co. Scale provided by the nests of cliff swallows at underside of bioherm and overhanging limestone ledge to left. The bioherm is about 50 feet thick. It has compressed the beds beneath, whereas those above show quaquaversal initial dips.

STROMATOLITIC BIOHERM IN THE POINT PEAK SHALE MEMBER OF THE WILBERNS FORMATION

FIGURE 1. POINT PEAK SHALE MEMBER OF WILBERNS FORMATION
Bioherm as in Plate 7.

FIGURE 2. VIEW OF UPPER SURFACE OF STROMATOLITIC BED
In lower part of biohermal zone of Point Peak shale member at south abutment of bridge over San Saba River near Camp San Saba, McCulloch Co.

FIGURE 3. CONFORMABLE CAMBRIAN-ORDOVICIAN CONTACT (NEAR MAN'S FEET)
In limestone sequence on Threadgill Creek upstream from Lange's Mill, Gillespie Co.

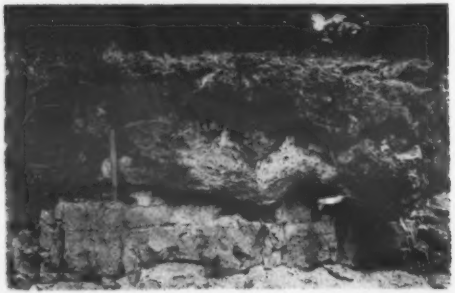

FIGURE 4. DISCONFORMABLE CAMBRIAN-ORDOVICIAN CONTACT
On west bank of Buffalo Creek, W. S. Porch ranch, San Saba Co. Very fine-grained dolomite of Pedernales dolomite member of Wilberns formation truncated by coarse-grained dolomite of Threadgill member of Tanyard formation.

cellently exposed Upper Cambrian section on Threadgill Creek in Gillespie County contains an almost complete sequence of late Upper Cambrian faunas; which, upon description, should become the standard of reference for the late Upper Cambrian faunas of the Llano uplift; the *Scaevogyra-Platycolpus* fauna has not been found in this section. This fauna appears to occur principally in stromatolitic bioherms, and these are conspicuously absent in the Threadgill Creek section. They are, however, common in the near-by Squaw Creek section, and their position can readily be projected into the Threadgill section.

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